Developing a Cost-Effective Solar Powered Vaccine Refrigeration Unit for Uttar Pradesh, India

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TABLE OF CONTENTS

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LIST OF FIGURES

LIST OF TABLES

***Abstract*—Critically underdeveloped countries often lack the technologies and properly established medical standards to meet the basic needs of their patients. According to numerous studies, high in-patient and infant mortality rates in these countries have been linked to inadequate medical treatment and unsanitary environments. The main barriers to obtaining the proper tools, supplies, and equipment needed to address these issues include the high initial costs, maintenance and upgrade costs, as well as accessibility of materials. This report focuses on a renewable energy solution to properly store vaccines for transport to rural communities in Northern India that lack the health infrastructure and access to medical care.**

The aim of this project was to develop a working prototype of a portable vaccine refrigeration unit powered by solar energy and battery storage. Experimental analysis showed that over a 48-hour period a single, one hundred-watt solar photovoltaic module was able to successfully provide adequate current to simultaneously charge a deep-cycle battery and power a commercial thermoelectric cooler for approximately twenty hours. This finding supports the limited viability of such a system under the approximate solar conditions of Uttar Pradesh, India during the winter months. Future research and tests using the data obtained from larger sized photovoltaic units and higher capacity energy storage units could possibly serve as the basis for the development of a more stable and robust unit with a higher degree of operability and autonomy.

***Index Terms*—Solar, Photovoltaic, Refrigeration, Battery, Vaccine, Autonomy, Cold-Chain, Medical, Thermal, MATLAB, LT-spice, Fusion 360, Renewable, Energy, India**

I. Introduction

Within the last decade, new records were set for global life expectancy which were largely due to reductions in infant mortality and disease prevention through vaccinations. While the global population continues to increase and the percentage of populations with access to medical care also sets new records, the number of individuals who still lack medical care remains at a high level. The analysis of this report focuses particularly on the state of Uttar Pradesh, India. India is the second most populated country in the world and is also one of the world's leading producers of vaccines. In recent years great progress has been made in the distribution of vaccines, including national events where hundreds of thousands of children are vaccinated in a single day. On the other hand, access to this nation's poorest populations remains elusive, and each year India reports hundreds of thousands of cases of preventable diseases such as polio, hepatitis B, and tuberculosis. There are societal and technical challenges in reaching these populations. One major challenge is the critically low access to education. Large groups of the population either lack the knowledge, do not understand the benefit, or even fear the idea of being vaccinated. Another major challenge is the lack of a cold chain infrastructure needed to effectively deliver vaccines to the poorest communities that are highly prone to vaccine-preventable diseases. This is where renewable energy engineering (REE) can make the greatest difference. The development of new clinics requires significant time, capital, and input from targeted communities. By taking advantage of the modular nature of renewable energy sources such as solar PV modules, medical workers can take portable vaccine coolers into densely populated and underserved communities with the greatest need.

This project analyzes the potential of using a battery-supported, solar-chargeable, portable vaccine refrigerator to fill in the gaps of the cold-chain infrastructure in Uttar Pradesh. The goal was to design a system that is cost-effective, portable, and one that fulfills the requirements of the Center for Disease Control (CDC) recommendations for secure vaccine storage.

A. Summary of the Problem

Based on the NREL report entitled "Renewable Energy for Rural Health Clinics (1998)", the "Cold Chain" is the infrastructure necessary for the distribution of vaccines. This system consists of medical workers who physically transport electric vaccine storage equipment designed to maintain a 2°- 8° C temperature range during transport of vaccines [1]. One challenge facing successful distribution of vaccines and the transport of other temperature sensitive medical items in developing areas is the technological shortcomings within an area's Cold Chain Infrastructure. The abundance of renewable energy technology in developed countries like the United States offers potential solutions for filling those gaps.

Current technologies for solar-powered vaccine refrigeration involve a Solar Direct Drive, where a refrigeration unit freezes a "water bank" that will act as a thermal regulator if the power goes out. These systems do not have batteries and tend to be more cost effective than fully relying on refrigeration systems for constant cooling. A vaccine refrigeration system with battery pack and a solar PV panel which supports additional electrical loads could be useful for a health clinic. Many rural clinics still rely on people carrying vaccines into isolated parts of the country, far away from electronic amenities of any kind. By foot or by mule, keeping samples chilled to a proper level is a constant concern for health practitioners.

The northern state of Uttar Pradesh, India was the region of consideration for this project. The team focused primarily on the rural districts of the state because of the high incident rate of child mortality due to vaccine preventable diseases (i.e., only 51% of children aged 12-23 months have basic coverage) [2]. A solar-powered unit would be practical for this location considering the high range of solar resource available. There was also adequate research information and resources that allowed the team to adjust the specifications of this technology to meet the meteorological and socioeconomic conditions in that area. Data from the World Health Organization (WHO) suggests that the need for vaccination is concentrated in the northern regions of Uttar Pradesh where the risk of disease is high, especially for vaccine preventable diseases like tuberculosis with more than 200,000 cases every year [3][4][5].

In Uttar Pradesh, tuberculosis, hepatitis B, and polio are common diseases that could be prevented through proper vaccine refrigeration (i.e., at a temperature between 2° - 8 °C) [6]. Rotavirus vaccine is also needed by the general population and could be stored safely at this temperature [5][6].

B. Purpose and Objectives of this Project

The main objectives of this project include the assessment of the technical and economic feasibility of implementing the proposed solar powered vaccine refrigeration units in areas within India that still have low vaccination rates, such as Uttar Pradesh. The team was focused on developing and building a prototype of the PV-system which includes a portable thermo-electric vaccine refrigeration unit. We also created an analysis of the logistical and social implications of implementing such a technology.

C. Proposed Solution to the Problem

The team set out to design a portable, battery-supported, solar-powered vaccine refrigerator that met CDC-recommended standards and was technically and economically feasible. The portable refrigeration system was intended to provide medical workers a means to transport vaccines into the densely populated, poor communities that are at greatest risk.

Our system sought to address both the rescue and developmental aspects of Uttar Pradesh's medical situation. A rescue (or relief) effort allowed the team to design a smaller and more portable system that would aid rural cold-chain vaccine transport methods. This system also requires less power than a full-sized medical grade system. An article from the Brookings Institution mentions that health clinics in India use a network of primary health centers (PHC) and community health centers (CHC). There are also subcenters that serve as a first contact between PHCs and CHCs for families in rural villages for general child health, immunity, and communicable disease treatment [7]. A solar powered vaccine refrigeration unit designed to be distributable for rescue efforts would effectively improve the storage technologies available to medical workers, allowing subcenters to provide higher quality or expanded vaccine administration services (i.e., this system would have a more relevant, immediate, and longer lasting impact on the rural districts in Uttar Pradesh).

Our project could potentially see a higher rate of success if it supports the local economy. Thus, incorporating a small-sized cell phone charging station and requiring users to pay a small fee for each recharge would help raise profits for clinics. It could also provide an opportunity for small businesses to rent (or purchase) PV equipment to provide customers with other services (i.e., charging, computer stations, etc.). Overall, the short-term impacts of this system would be focused on rescue, but the long-term impacts would be beneficial for economic development.

II. Project Technology Description

A. Technology Overview

Students are building a solar powered vaccine refrigeration (SPVR) unit prototype for small clinics and subcenters that would be portable, lightweight, cost-effective, and provide the maximum utility relative to its size. The primary loads of the system include a charge controller, thermoelectric cooler, and a DC thermostat. While the charge controller and DC thermostat draw considerably less current than the cooler, they are essential to the operation of the unit. The charge controller protects the system from overvoltage, overcurrent, overheating, short circuit, reverse polarity, and other electrical failure scenarios. The DC thermostat allows the user to set the desired temperature range of the thermoelectric cooler. Once the desired temperature range has been achieved, the thermostat deenergizes the cooler. Secondary loads can be attached to the charge controller which has two USB ports with a standard 500 mA current output [8]. This feature enables the charging of small electronic devices and mobile phones.

B. Design Summary

Due to economic restraints, the team had to acquire prototype components that could fulfill most of the requirements of the SPVR system at the lowest available cost. These limitations led the group to use the PV trainer module on campus, made accessible by Richard Ellis. The PV trainer module significantly reduced spending since several of the necessary components of the SPVR unit were already included (i.e., such as the PV module, charge controller, DIN rails, and fuse components). However, it does not represent the model that would be employed in the field. An ideal system would house electrical components within a centralized container so that most electrical connections would not be exposed to the elements. This container would house the battery, charge controller, and DC thermostat.

A sealed lead acid (SLA) battery was chosen because this energy storage technology is universally used and comes at a lower cost than lithium ion batteries. SLA technology also requires less regular maintenance than flooded lead acid batteries, making it a more robust option [9]. The prototype refrigeration unit used during testing was the Igloo Iceless thermoelectric (TE) cooler. This unit was selected because it was cost-free (i.e., this was a donated item); had a larger carrying capacity compared to other mini-coolers in the market; and used an internal temperature reduction system that was slightly more powerful than other mini-coolers in the market. The Igloo Iceless TE cooler did not have any shelving on which to place the vaccines. To compensate, students placed the vaccine vials in a modified plastic basket. The bottom of this basket had small rectangular holes covered with paper towels to allow a certain degree of cool air flow to the vaccine vials from the bottom. It also had a wooden grill near the top of the basket to hold any loads placed on top of the basket. The layering of the thermal mass conformed to the CDC recommendations for the refrigeration and transport of vaccines. Chilled water bottles lined the bottom of the cooler; a basket was placed on top of those bottles; and another layer of chilled water bottles placed on top of the wooden grill of the basket. Photos in Appendix I show the cooler setup and the layout of the system. The diagram in Appendix E illustrates the layout of principle components of the SPVR unit, with electrical connections included in the figure.

C. Approach and Methodology

This project consisted of three major development phases with five working areas of focus. All members of the project team were tasked to perform research, planning & design, development, and testing for one or more of these areas of focus:

- Solar Power System (Energy Generation)
- Battery System (Energy Storage)
- Vaccine Refrigeration (Electric Load)
- Accessory Charging Station (Secondary Load)
- System Modelling and Cost-Benefit Analysis

The first development phase focused on discussion and agreement on the project focus and direction. Once an agreement was reached, administrative tasks such as teamwork hours, scheduling, and meetings were planned. The constraints that could affect project accomplishments for each phase included delays in the acquisition of materials; lack of funds; material availability; personal and academic obligations; time availability for each team member; errors and revisions; faculty availability; equipment availability; unexpected failures in building tools and equipment; and project revisions recommended by faculty members. For a project of this scale, approximately 80% of the delays were attributed to these unforeseen events. Dynamic time management methods were necessary to optimize the use of limited project development time.

The first phase also focused on research into the five system components. This involved a thorough review and analysis of the literature associated with the component technologies currently available in the market. Team members will also be responsible for enhancing their knowledge in the areas of material science, photovoltaic (PV) systems, medical standards, and economics to better understand the design of the system. Prior knowledge and information from the following courses were needed during the planning phase of this project:

- PV Systems
- Materials for Renewable Energy Applications
- Thermodynamics & Heat Transfer
- Costing Renewable Energy

The team created and revised several drafts of the PV vaccine refrigeration system design with the intent of keeping the system simple, maintainable, and cost-effective. Once a final model had been agreed upon, the team discussed the development of a small-scale prototype of the actual SPVR unit. During this phase, students also documented their observations and findings and began creating a revisable draft of the first project progress report.

The second developmental phase was an iterative process involving multiple revisions on the prototype design or system testing methods. Once the final model and method of testing was agreed upon, the prototype of the SPVR unit was developed. Team members planned and implemented various tests to simulate the expected climate in Uttar Pradesh. Our team ensured that the safety protocols of the power lab at Oregon Tech and all safety regulations were followed (Appendix O). Our team began characterizing the limitations and strengths of the device which provided a basis for the economic feasibility analysis. After testing various parameters of the device (Appendix J), the team reported its findings in the second project progress report.

The third developmental phase was originally planned as a check on the tests conducted in the second phase of the project. However, due to the COVID-19 situation, the team decided to cancel further testing and analyze the existing data obtained from previous experimental tests. Throughout the process, the appropriate faculty members were informed of the progress and intents of the team.

Economics played a major role in the guiding the group's choice of materials for this project. The total budget available to the team was $400 which included $30 from lab fees per student over three terms ($10/term) and a $70 individual contribution per team member. To limit spending, the group decided to use the PV trainer module mentioned previously. This trainer system was convenient for experimental testing and data collection, as all electrical connections were readily visible and accessible. This feature made it easy to verify that all connections were properly configured.

The factors considered when creating the testing parameters for this project included climate and solar radiation research data; electric and thermal performance of the thermoelectric cooler; as well as charging & discharging characteristics. Calculations were performed in MATLAB to help determine characteristics such as the R value of the Igloo cooler as well as the minimum battery sizing requirement based on the power requirements of the Igloo cooler.

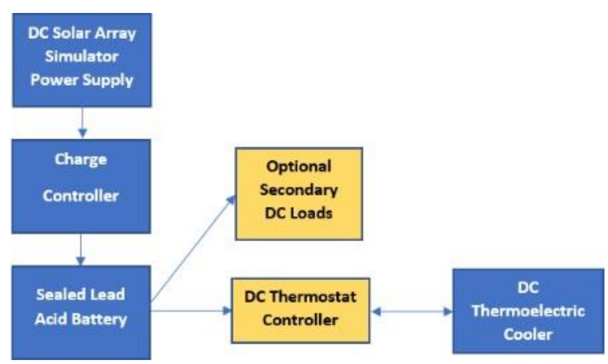

Fig. 1: Block Diagram of SPVR System Interconnections.

D. Components & Testing Equipment

The main electronic components, equipment, and tools used in Phase 2 of the project are shown below. The dimensions of the main components are listed in Appendix L. For the full list of materials and equipment used for this project, please refer to Appendix G.

- PV System Components
  - Renogy 100D 100 W PV panel (2017 version)
  - ExpertPower 12 V, 55 Ah Sealed Lead Acid Battery

- Igloo 28-Quart Iceless Thermoelectric Cooler
- LM YN DC 12 V Thermostat Module
- ALLPOWERS Solar Charge Controller (20 Amp)
- Faylapa CS-579B4 12-Way Fuse Block
- 18 AWG Conductor Wire

* Testing Equipment
  - BK Precision PVS60085MR Programmable DC Power Supply (DC Solar Array Simulator (SAS) Power Supply)
  - BK Precision 8512 DC Electronic Load
  - Fluke 289 DMM/FVF FlukeView Forms Combo Kit
  - WILLHI 110 V Temperature Controller/Digital Thermostat
  - SensorPUSH Wireless Temperature and Hygrometer Sensor (or PUSH Sensor)
  - Duracell Ultra 3.8 A, 12 V Battery Charger
  - Trip-Lite AC Surge Suppressor Outlet (for Component/Equipment Protection)
  - 12 V AC Converter Adapter for Igloo cooler
* System Assembly Tools
  - Ratchet Wrench Assorted Sizes
  - DIN Rail Screwdriver
  - Wire Connection Crimper
  - Heavy-duty Boxcutter
  - DeWalt Portable Drill
  - Wire Cutter & Stripper
  - Measuring Tape

E. Healthcare and Technology-Related Ethical Concerns

The temperature probe of the DC thermostat of the SPVR unit would need to be regularly calibrated against a high-quality thermometer with a low tolerance rating to ensure that vaccines are consistently being maintained within the prescribed temperature range. Without this safeguard, there is less certainty that the vaccinations would be consistently administered under proper temperature conditions to ensure maximum potency.

Owners of the SPVR technology would be entitled to assess a fee for individuals using the mobile phone charging capability of the charge controller. The fee should be assessed at a value that is lower than the market cost of electricity, thereby making it available to people of lesser social status. However, with the current prototype situation, this feature may not be available unless solar conditions are optimal (1000 W/m^2) and a larger PV panel is used in the SPVR unit.

Further testing could be performed to determine whether the prototype model is capable of supplying power to additional loads. The possibility exists for consumers to modify this product beyond its nominal operating specifications which raises concerns for the safety of the user and the quality of the primary load operation for the user. In addition, once the technology reaches the end of its warranty or lifespan, consumers may try to salvage materials to use in other technologies or replace parts with components that do not conform with internationally recognized medical standards. External or internal enhancements to the vaccine refrigeration unit or the solar unit may also change or reduce the capabilities of this technology.

F. Project Milestones

During phase one of the project, the team prepared for calculation and simulation work that began in November 2019 and was completed by January 2020. Experimental testing began on January 30, 2020. The updated computer simulations and experimental trials had been completed by March 19, 2020. A summary covering the main analysis of the experimental trials is presented in the technical feasibility section of this report. Due to precautionary measures that the administration of OIT had taken to limit the spread of COVID-19, the team had decided to conclude further testing as of April 7, 2020. A full analysis and interpretation of the results from phase two was successfully completed by May 3, 2020.

III. Technical Feasibility

The components for the ideal design were chosen because they met the minimum calculated design specifications. The goal was to develop a prototype system that provides enough power, vaccine storage space, and portability while meeting the physical demands of being deployed in Uttar Pradesh, India. The main consideration for a working fridge system is the ability of the thermoelectric generator (TEG) to maintain the required 2° – 8°C to keep the Polio, Hepatitis B, and Tuberculosis vaccines in proper storage conditions. Several guidelines from the WHO set standards for vaccine storage that require the 0.5 mL vials to be 2 cm apart to allow proper airflow and temperature control [10]. Economic constraints limited the team from acquiring the principal components for a more robust design and ideal testing setup (see Technical Feasibility part D). The modelling work and experimental data included in this section reflects the system that was built using the components from the economical design.

A. Technical Limitations

The Igloo cooler does not have internal shelving or barriers to separate vaccine containers from one another. The team designed a custom rack to secure the vaccine vials in place while accommodating thermal mass. According to the CDC "Vaccine Storage and Handing Toolkit" document, vaccines stored in refrigerators must have thermal mass (water bottles) on the top rack, bottom rack, and door racks [11]. Considering that the Igloo TEC has a more compact space, the team was only able to accommodate a top and bottom layer of water bottles. The positioning of the thermal mass also conformed to the CDC document "Packing Vaccines for Transport During Emergencies" [12].

Using high quality medical grade vaccines and vaccine potency testing equipment as part of the thermoelectric cooler tests was beyond the budget for this project. Even if such materials could be obtained, this would likely make implementation of this technology cost-prohibitive for its intended application. The climate conditions in Uttar Pradesh, coupled

with the performance characteristics of the Igloo TEC and considerations for needed vaccine temperature control, render the SPVR prototype functional only during the three coolest months of the year (i.e., December, January, and February). Even though the solar conditions are not optimal during these three months, the climate is notably drier than other parts of the year, which is more ideal for using the SPVR unit. Testing the unit in Uttar Pradesh was beyond the intended economic and physical scope of this project.

The room in which the system testing was performed was consistently at a temperature of approximately 20°C. This consistency does not align with the temperature fluctuations experienced over a typical winter day in Uttar Pradesh. To receive data that is more reflective of true climate conditions experienced in mobile applications, the SPVR unit must be tested outdoors. The highly variable weather conditions and amount of solar radiation in Allahabad, Uttar Pradesh, India during the winter season required the use of a DC load simulator and programmable DC variable solar power supply simulator equipment to provide constancy in all power measurements. Testing the SPVR prototype unit outside under direct sun conditions would have been a more optimal direction for the project tests, but a 24-hour test period under clear sky conditions was not possible.

The portability of the SPVR unit has several limitations that originate from the equipment used in the prototype model. For one, the rigid frame of the 100 W PV panel makes it less easily carried than the desired solar suitcase PV panel [13]. As the name of that panel implies, the flexible design allows it to be folded and carried by a handle. The weight of the SLA battery is an inherent limitation to true portability. This chemistry is significantly heavier than that of its lithium ion counterparts. In general, an SLA battery with the same amp-hour capacity as a Li-ion battery weighs twice as much [14]. While the cooler could be detached from power and be temporarily used as a traditional cooler, the complete SPVR unit would undoubtedly need to be transported by a pack animal or vehicle.

B. Theoretical Performance Evaluation

The PV System Sizing Excel Spreadsheet calculations (Appendix B) and the MATLAB calculations (Appendix C) allowed the team to determine that a 55 Ah battery would allow for the system to run for a complete 24-hour cycle without any solar power under ideal conditions. In the scenario where there was no power generation from the PV panel for more than one day, the system would not be capable to support any loads. The team had to consider the trade-offs of system portability to system autonomy. Considering the economic constraints imposed on this project, the team chose a 55 Ah battery which met the minimum requirements of the calculated PV system sizing. The MATLAB results also provided insight into the heat flux of the Igloo cooler under ideal conditions (6.776 W/m²) which was also used as a basis for comparison for the Fusion 360 thermal simulation analysis described later in this sub-section.

The charge controller unit and SPVR system was modeled in LTSpice to verify expected electrical performance. The team used the LTSpice model of a PWM charge controller to approximate the ALLPOWERS charge controller used in the SPVR prototype [15]. As can be seen in Appendix A, the DC thermostat is not included in the simulated model. However, the current draw of the ALLPOWERS charge controller combined with the DC thermostat approximates the performance of the charge controller used in the simulation (i.e., 160 mA, as stated from the user manuals, versus 185 mA, when run in the simulation).

The main assumptions for the LTspice simulation were that the maximum solar conditions corresponded with the short-circuit current $(I_{sc} = 5.75\ A \approx 5.8\ A)$ in the simulation. The LTspice model was based on a generic charge controller that approximated PWM current & voltage control due to the lack of a specific circuit diagram for the ALLPOWERS controller. Maximum solar irradiance was assumed to be 1000 W/m2. As indicated in Appendix A (Fig. 5), the simulated current is shown entering the battery. Under maximum solar irradiation conditions, approximately 710 mA of current was permitted by the charge controller into the battery. A sweep analysis was performed to determine the point where current flowing from the charge controller (CC) to the battery changed from a negative value (i.e., CC supplying power to the load) to a positive value (i.e., CC charging and supplying power to the load). The results of this analysis showed that an input current above 5.055 A would permit current to flow to the load and the battery. The solar irradiance conditions for the switch from CC-to-load to CC-to-load & battery was determined to be 871 W/m² after equating the input current (i.e., 5.055 A) to short- circuit current ratio with the ratio of the input solar irradiance to the maximum irradiance.

The MATLAB calculations roughly yielded similar results to the LTspice simulations in terms of the solar irradiance conditions needed for the charge controller to switch the current flow from CC-to-load to CC-to-load & battery. For these calculations, the maximum input current to the charge controller during ideal solar irradiance conditions was assumed to be equal to the maximum operating current of the panel (I_{op} = 5.29 A). The switching current boundary (i.e., CC-to-load to CC-to-load & battery) was assumed to be equal to maximum typical load draw of the Igloo cooler (i.e., 4.8 A). Based on these assumptions, the solar irradiance conditions for the switch from CC-to-load to CC-to-load & battery was determined to be approximately 907 W/m². The current to the battery under optimal solar conditions was determined to be 490 mA. The main limitation to the MATLAB calculations was the lack of information regarding the current flow switching algorithm or calculation of the ALLPOWERS charge controller. It should be noted that this model does not take into consideration mobile phone charging through the USB ports on the charge controller. This would be applied as an additional load on the system, resulting in a higher probability that the battery would have a decreased recharge period. A more efficient PV module would theoretically be able offer better

power output; however, this would likely come from a larger, heavier solid-frame PV panel, thereby further affecting the portability of the SPVR unit.

The thermal simulation of the Igloo cooler focused on showing how the refrigeration system behaves under different thermal loads. Three scenarios were tested to simulate different conditions that the cooler would operate in, specifically in Uttar Pradesh during the month of January. The cooler has a surface area of approximately 0.786 m^2, which was measured through Fusion 360 modeling (Appendix D, Fig. 11) and a power draw of approximately 60 W. While no official documentation was found that shows the efficiency of the cooler, an approximation of 12.5% was assumed [16]. This was a major assumption to make prior to physical testing and does affect the projected outcomes from the thermal simulation. One limitation on the use of the thermal simulations in Fusion 360 was that only static conditions could be modeled which limited the accuracy of the results.

A CAD model was created in Fusion 360 that was based off the measurements of the Igloo cooler. Several compromises had to be made to the CAD model to simplify the system. The cooler is powered by a thermoelectric generator (TEG) and uses a fan to exhaust excess heat from the system. Due to limitations of the software, the fan had to be removed from the thermal simulations. Another alteration was to the lid of the cooler, which is shown to be solid, though the actual cooler has a chamber in the lid that allows air to flow from the fan to the TEG.

The thermal loads were comprised of two sources of heat: the interior chamber and the exterior shell. The interior chamber walls had an applied temperature source with the assumption that the chamber was at a constant temperature. The exterior walls had a convective thermal source that was applied to simulate the air moving around the cooler. By using the simulation function of Fusion 360, a rough estimation of the heat leaving the cooler can be modeled and estimated at various points on the surface of the fridge. The main consideration for these tests were to replicate the physical materials that makeup the walls of the fridge as well as the insulation material located in the interior of the fridge. While general dimensions were found, it was not clear how thick the individual layers of material are, so an approximation of 0.344 in per layer was made (Appendix P, Fig. 27). The interior and outer layers are made up of polypropylene plastic which serves as a hard, light shell that protects the cooler from physical impact. A middle layer of polyurethane foam acts as the insulator for the system, reducing the heat flux that radiates through the cooler walls. The material properties of the three layers are accurately reflected in the Fusion 360 design based on the stored physical material properties that the program uses to run physical tests on 3D models.

Prior to beginning the simulations, the heat transfer coefficient (h_c, W/m^2 K) had to be calculated for the system. This was done using (1), where Q represents the heat flux, A represents the area of the cooler wall, and ΔT represents the difference between the exterior and interior temperature of the TEC. The heat transfer coefficient represents the heat flux through a surface based on the change in temperature between the ambient environment and the exterior walls of the cooler and was found by analyzing the maximum operating temperature conditions. It was assumed that during the maximum operating temperatures, the cooler will have to run continuously to keep the interior at or below 8 °C. Given the approximate efficiency of the cooler to be 12.5% and a power draw of 60 W, this leads to 7.5 W of energy leaving the cooler. Based on these assumptions, h_c was found to be 0.4769 W/m^2 K and was assumed to be constant throughout all three tests. By keeping the thermal coefficient constant, the amount of energy leaving the system could be calculated for each load.

$$h_c = Q/(A\Delta T) \tag{1}$$

1) Load 1: Indoor Conditions

The first load simulation performed was for the indoor operating conditions ($T_{interior}$ = 5 °C, $T_{ambient}$ = 20 °C) for the cooler. These conditions assumed the cooler would be in a temperature-controlled room out of direct sunlight and away from the wall to allow proper air intake (i.e., rural healthcare clinic or doctor's office). This would result in a low power draw since the cooler would not need to function for long periods of time to maintain its internal temperature. If we assume that h_c is constant, 5.625 W of heat are expected to leave the system. This would suggest that the total system draw, with an efficiency of 12.5%, would need a total 45 W to power the thermoelectric cooler under this load based on (2).

$$Q = h_c A \Delta T \tag{2}$$

The heat flux thermal simulation of Load 1 (Appendix P, Fig. 28), shows the cooler blue region being more insulated than yellow warmer region. As was expected, the cooler shows a symmetric profile in heat flux through the exterior walls. The heat flux through each wall and bottom of the cooler was calculated to be approximately 6.0 W/m^2 while the lid had a lower heat flux of approximately 2.2 W/m^2. In comparison, the MATLAB calculations for the walls of the cooler yielded a heat flux value of 6.776 W/m^2. Whereas no official documentation was found regarding the number of pairs of thermoelectric current (N-value), this value was assumed to be 100,000. This was another major assumption to make when calculating the TEC heat flux using MATLAB. As was expected, the seam where the lid rests on the cooler allows for the greatest heat flux (approximately 18 W/m^2) since the seal is not airtight.

2) Load 2: Maximum Operating Temperature

The second thermal simulation studied how the system behaved under the maximum operating temperature ($T_{interior}$ = 8 °C, $T_{ambient}$ = 28 °C). Since the cooler is limited to only being able to lower its internal temperature to -20 °C below ambient temperature, the maximum operating conditions for this cooler would be 28 °C. The vaccines that were being studied must be stored between 2 – 8 °C. By allowing the

temperature to rise or fall out of this range, the potency of the vaccines may be reduced. It is expected that the cooler would have highest power draw under these load conditions since the thermoelectric generator would have to be in constant operation to maintain the required 8 °C internal temperature. The thermal results for the maximum operating temperature are shown in Appendix P, Figure 29. Similar to the first test, the walls and bottom of the cooler showed a consistent heat flux of approximately 8.0 W/m² and a lower value (3.0 W/m²) for the exterior surface of the lid. The seams showed the highest heat flux (approximately 21 W/m²). Based on (1), the heat flux through the system was estimated to be 7.50 W/m² with a total power draw of 60 W.

3) Load 3: January in Uttar Pradesh

For the final load simulation, the operating conditions of Uttar Pradesh were approximated to be 16 °C to simulate the average temperature between night and day conditions. Similarly, a 5 °C interior temperature was chosen to provide a buffer for the vaccines in case of temperature changes. The temperature change in the third load was the lowest in comparison to the previous load simulations which suggests that the power demand for this simulation would also be reduced.

The final thermal simulation is shown in Fig. 2. The exterior walls of the main body of the cooler show an approximate heat flux of 4.4 W/m² through their center while the lid has a lower heat flux of approximately 1.7 W/m². As with previous models, the seams between the lid and the main body showed the highest heat flux of approximately 11 W/m². Assuming a constant h_c value of 0.4769 W/m²K, equation 1 was used to find the total heat leaving of the system under load 3 conditions to be 4.14 W. By using equation 2 the total power of the system was calculated to be 33 W.

The three simulations showed that the heat flux through the Igloo Iceless 28-quart TEC was determined based on the change in temperature between the environment and the interior chamber. The third load simulation showed the lowest power consumption from the cooler due to the reduced temperature differential. The second load simulation showed the maximum power that the system would require to operate the load continuously. As can be seen, there is a large variance in the amount of power that is required to maintain a constant internal temperature which creates a large drain on the overall battery system of the SPVR unit since it must be sized to consider this increased demand.

Further refinement to the thermal simulations could be done in future research to more accurately model the heat flux of the cooler. Adding a fan and accurately modeling the TEG subsystem would provide a more accurate profile of the cooler and allow for further refinement in other subsystems (i.e., batteries and solar panels). While the interior temperature was modeled to be constant the experimental results show that the temperature gradient within the interior of the cooler could be modeled for more accurate results. Similarly, the vaccine vials that are located within the cooler could be added to the thermal model to provide a more comprehensive thermal load analysis that more accurately represents the system.

C. Empirical Performance Evaluation

In order to characterize the physical and electrical capabilities of this system, the team developed three types of tests which included a load test, battery test, and full-PV system test. These tests focused on evaluating several parameters such as temperature, voltage, current, and load performance stability. These tests are listed below. Appendix M provides detailed information on the procedures for each of these tests.

- Load Test 1 (TEC Operation Check)
- Load Test 2 (TEC Thermal Mass Observations)
- Load Test 3 (CDC-Based Vaccine Storage Setup)
- Battery Discharging Test
- 24-hr Full PV System and Load Test
- 48-hr Full PV System and Load Test 1
- 48-hr Full PV System and Load Test 2

The development of these tests was based on a detailed list of test parameters (Appendix N) and testing equipment listed in Section II (D). The main limitations of this performance evaluation were the tolerance of the measurement equipment; the amount of component parameters the team could test; and the number of tests that could be performed with the limited financial and time resources. Based on a brief time and motion study, the team determined that conducting the essential tests directly relating to the storage of vaccines during transport would be sufficient to support the analysis & design for a workable prototype of a system that could potentially be deployed in Uttar Pradesh.

The team also decided that the main measurement device for the SPVR tests would be the Fluke 289 multimeter because of the ease of use, rugged construction, and detailed measurement data records. The secondary measurement device would be the wireless PUSH sensor which would mainly be used for the first load test (i.e., for TEC functionality) and serve as a backup temperature sensor for load tests 2 and 3. In addition, the BK Precision PVS60085MR was used to simulate solar input for all full PV system tests.

The time scales in the resulting graphs from the team's system tests (Appendix Q), with the exception of the second 48-hour test, represent the actual, non-scaled experimentation times. The graph of the second 48-hour test provides the results for a hypothetical solar day with a 0-hour start time and follows a non-scaled, 24-hour time basis. Please note that the range of x-axis (time) values for all of the load tests have been chosen so that the results of these tests could be compared within the same time frame.

1) Load Test 1 (TEC Operation Check)

For this load test, temperature measurement data from the PUSH sensors located at the top of the cooler were consistently higher than the bottom of the cooler by an average of 1-2 ºC (Appendix Q, Fig. 30-31). Thus, the temperature measurements at the top of the cooler were used to determine the length of time that the cooler was able to maintain a 2-8 ºC temperature range. Based on these measurements (Appendix Q, Fig. 30), the internal temperature of the top

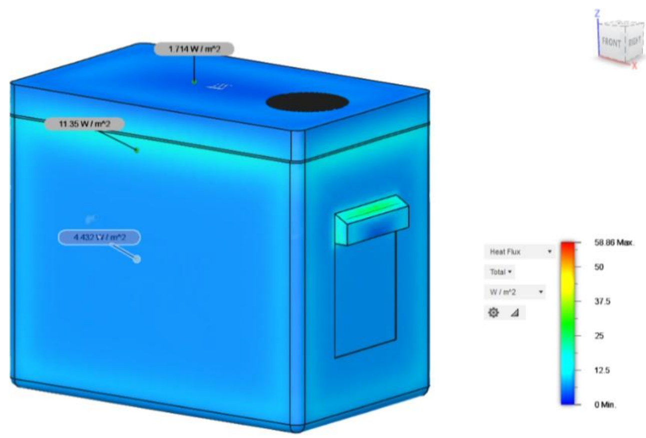

Fig. 2: Fusion 360 thermal simulation (Scenario 3) showing magnitude of the heat flux through exterior wall of the cooler assuming approximate temperature conditions for Uttar Pradesh in January.

of the cooler decreased from room temperature (20 ºC) to approximately 7 ºC within a period of about 3 hours. The internal temperature of the cooler remained at 7 ºC (± 0.9 ºC) for a period of approximately 6.5 hours. For the purposes of this test, the cooler functioned without any power interruptions or temperature inconsistencies.

After this period of temperature stability, the team turned off the power to the TEC at 6:25 PM. The internal temperature of the top of the cooler exceeded the 8 ºC vaccine storage temperature limit after approximately 12 minutes. In contrast, the bottom of the cooler took approximately 20 minutes to exceed this limit. The team also found that bottom of the thermoelectric cooler was only able to reduce its temperature by approximately 14 ºC below ambient temperature (i.e., compared to the rated temperature reduction of 20 ºC). In addition, the rapid rise in temperature after the power to the TEC was turned off indicated that there was an external source of heat that influenced the internal temperature of the cooler. The team made an initial inference that the small gaps where cooler lid touched the top of the cooler were allowing the warmer ambient air into the cooler which may have resulted in rapid temperature increases after power to the TEC was removed.

2) Load Test 2 (TEC Thermal Mass Observations)

The main purpose of this test was to determine the temperature behavior of the cooler with thermal mass. Before including the thermal mass, the rate at which the internal cooler ceiling temperature decreased was similar to the PUSH sensor tests from load test 1. Between 10:30 AM and 1:00 PM this rate of decrease was 4 ºC (± 1 ºC) every 22 minutes (Appendix Q, Fig. 33). A similar trend was observed for the bottom of the cooler (Appendix Q, Fig. 34).

During the second load test, the team noted a positive temperature spike at the top of the cooler which started at 2:40 PM. This was caused by the inclusion of thermal mass which consisted of 31 frozen vaccine vials and 4 frozen bottles of water (i.e., the thermal mass was determined to be at approximately -2.7 °C). Within about 22 minutes of including the thermal mass, the temperature reached 13 ºC (± 0.1 ºC). In contrast, there was also a negative temperature spike at the bottom of the cooler where temperatures decreased to -2.7 °C (± 0.1 ºC).

Three hours after the thermal mass was included, the temperature at the top of the cooler remained relatively stable at approximately 14.3 °C. Whereas, the temperature at the bottom of the cooler was at about 4 °C and gradually increasing at a rate of 0.5 °C (± 0.2 ºC) every 40 minutes. From this data trend, the team inferred with a high degree of certainty that the thermal mass had created a region of dense, cold air at the bottom of the cooler which forced the warmer air to the top of the cooler. In addition, the small gap in the cooler lid (i.e., created from the thermocouple wires entering the cooler), permitted small amounts of ambient air into the cooler which may have accounted for the slight increase in temperature over a three-hour period.

3) Load Test 3 (CDC-Based Vaccine Storage Setup)

For this test, the team used water bottles and vaccine vials that were at a temperature of approximately 2 °C. One hour and thirty minutes after the thermal mass was included, the temperature of the top of the cooler stabilized at 5 °C (± 0.2 ºC) and the temperature at the bottom of the cooler had stabilized at 6 °C (± 0.1 ºC) (Appendix Q, Fig. 33-34). Over a period of approximately 4.5 hours, the temperature of the top and bottom of the cooler decreased by 1 ºC (± 0.3 ºC). When power to the cooler was turned off at 4:50 PM, it took approximately two hours for the bottom of the cooler to exceed the 8 ºC vaccine storage temperature limit. Whereas, the top of the cooler took approximately 45 minutes to reach the vaccine storage temperature limit.

From these results, the team noted that the bottom of the cooler was able to maintain a 2-8 ºC temperature range for a significantly longer period of time compared to load test 1. The team inferred with a high degree of certainty that these improvements in temperature stability were attributed to the

addition of a flexible foam window seal on the area where the lid rests on the cooler as well as the inclusion of thermal mass. The seal greatly reduced the amount of ambient air that could enter into the cooler resulting in a higher degree of temperature stability.

The temperature of the vaccine vials (Appendix Q, Fig. 36) also followed the same trends as the top and bottom portion of the cooler. Between 11:40 AM and 5:00 PM, the vial temperatures were consistently 1°C (± 1.2 ºC) below the top interior temperature of the cooler and 2°C (± 1.2 ºC) below the bottom interior temperature of the cooler. This supports the team's inference that the seal and surrounding thermal mass (i.e., water bottles) were a significant factor in maintaining temperature stability. This finding further supports the thermal simulation (Fig. 2) which indicates the main source of internal-external air flow was the seam of the cooler.

A comparison graph was developed to determine the correlation between the interior temperature of the TEC and the influence of the TEG on the internal temperature of the upper portion of the cooler (Appendix Q, Fig. 32 and 35). The team noted that a decrease in the internal cooler temperature was followed by a corresponding increase in the temperature of the heat sink due to the electrically induced temperature gradient in the TEG. This finding confirms the relationship between the temperature towards the top of the cooler and the TEC heat sink.

4) Battery Discharging Test

The main objective for this test was to determine whether a 55 Ah, 12 V sealed lead-acid battery would reach its rated depth of discharge (DOD) within a 24-hour period of time. For this test, the team set the DC load simulator to simulate a load that draws 12 V and 4.8 A which represents the maximum typical power draw of the cooler. Once the rated depth of discharge (11.6 V) had been reached, the DC load simulator would automatically shut down. The battery was initially charged to 12.578 V using the Duracell Ultra charger. After a 24-hour period, the battery was measured to have a voltage of 11.695 V.

Based on the calculated autonomy and expected duration of load operation per day, the result of this test matched the team's expectation that the rated DOD (of approximately 11.6 V) would be reached before the 24-hour period was completed. However, this result represents the ideal scenario where the battery discharges at a constant rate.

5) 24-Hour Full PV System Test and Load Test

For this test, the main objective was to determine the functionality of the PV system and the DC power supply. The graphical results for the 24-hour full system test (Appendix Q, Fig. 37) show that the battery voltage and current input to the cooler remained constant (i.e., at approximately 13 V and 4.5 A, from 5:30 PM to 3:00 PM the next day) when the DC SAS supplied power at a preset power curve which conformed with the EN50530 European testing standard. The temperature of the Igloo cooler remained under 8 °C for the duration of the test. Furthermore, the optimal vaccine temperature of 4-6 °C was maintained for approximately 10.5 hours (i.e., from 3:16 AM to 1:46 PM).

These results illustrate that the refrigeration unit could keep the appropriate vaccine temperature with a power input that conforms to EN50530 testing standards (i.e., involving a preset, simulated solar irradiation intensity pattern fluctuating between 30% to 100% of 100 $W/m^2/s$) [17].

6) 48-Hour Full PV System and Load Test 1

The first 48-hr test was run with a DC SAS Power Supply program that supplied a total of 540 Wh/day to the SPVR unit (Appendix Q, Fig. 38). This test compared the temperature of the cooler, the voltage level of the battery, the load current, and the power supplied by the DC SAS Power Supply over each 24-hour cycle. A DC thermostat was utilized to maintain the vaccine vial temperature between 2-8 °C.

The results of this test indicate that the DC thermostat and cooler setup only began to draw current once it reached the set temperature limit of 8 °C. The vaccine vial temperature remained within the acceptable range of 6.2-8° C for a total of 37.25 hours. When the first simulated night-time condition started at 4:49 AM, there was approximately a 40-minute gap where the measured load current was zero. The team inferred with a high degree of certainty that the cooler turned off in step with the power supply and did not immediately draw power from the battery. Once the cooler began to operate on battery power, the data shows that the battery voltage was decreasing at a rate of approximately 0.2 V/h which lasted for approximately 11 hours, followed by a sharp voltage decline (lasting for 2.8 hours at a rate of about 1.17 V/h) as the battery approached its maximum depth of discharge. After this period, the battery was able to return to a charge level of approximately 11.8 V at 11:34 PM (during the second simulated solar day). The cooler continued to function while drawing power from the DC SAS power supply as it operated for the second and final (24-hour) cycle. After the DC power supply turned off approximately one hour after 3:19 AM (i.e., to simulate the second night-time conditions), the battery rapidly discharged and was not able to supply adequate power to keep the load operating. This is evident by the lack of measured current through the load and the continuously increasing vaccine vial temperatures after the battery reached its deep-discharge level (i.e., 4.5 V approximately 1.5 hours after night-time conditions started).

From these results, the team determined that the battery would be able to supply power and keep the cooler operating sufficiently for approximately 11 hours. This first test provided promising results for the limited operation of this system in Uttar Pradesh. However, it should be noted that the solar curve was developed using the maximum current and voltage output of the panel and the length of daylight in Allahabad. It should also be noted that the battery would have to enter a state of deep discharge to achieve 11 hours of cooler operation. In practical applications, excessive deep-cycling could significantly reduce the cycle life of an SLA battery (e.g., from six months to one month of constant use).

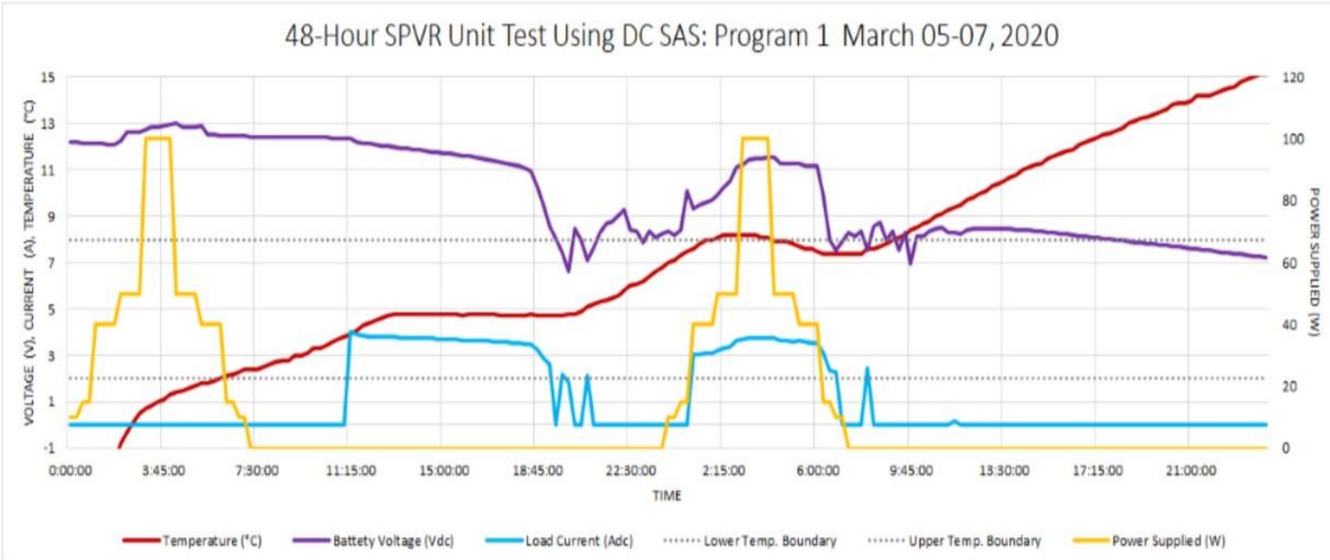

Fig. 3: Second 48-hr test of the SPVR unit. The system was provided with a total simulated solar power input of 335 Wh per day.

7) 48-Hour Full PV System and Load Test 2

The second 48-hr test showed that the SPVR system was able to remain within the proper vaccine storage temperature range of 2-8 °C for 32 hours (Fig. 3). Unlike the first 48-hour test, the DC SAS Power Supply program during this test provided a total of 335 Wh/day to the PV module (i.e., a reduction of 205 Wh compared to the previous 48-hr test). This adjustment to the total power input was made based on the group's change in understanding of average peak sun hours during January in Allahabad, Uttar Pradesh (Appendix K). During this 48-hour test, the thermal mass placed inside the cooler was at a temperature below the cooler's 2-8 °C operating temperature. The first time where the temperature was above 2 °C was approximately 6.25 hours after beginning the test (6:15 AM). For the purposes of simulating the cold-chain conditions, we considered this point in time as the true starting point of the test where the vaccine temperature data was valid.

The graph of this test also shows that during the first simulated solar day, the cooler remained off. At about 11.25 hours into test, the cooler reached the upper temperature limit for vaccine storage and began to draw power from the battery. The vaccine vial temperature was maintained between 2-8 °C for 20 hours (6:00 AM of day 1 to 2:00 PM of day 2). The team noted that the cooler was only able to operate under battery power for approximately 7 hours before the battery reached a depth of discharge too low to supply power to the load. The cooler remained off after this period, with a steady rate of temperature increase of about 0.5 °C/h, until the DC SAS power supply began to supply enough power during its second cycle, at which point the cooler temperature returned to the 2-8 °C range for 5 hours (i.e., from 4:15 AM to 9:15 AM during the second simulated solar day). The cooler ceased to operate once the power supply turned off because the battery did not receive enough power to operate the load and recharge during the second power cycle. As the graph indicates, the battery voltage was significantly below its operational range, and the temperature continuously increased at about 0.5 °C/h. Similar to the previous 48-hour test, it should be noted that the battery would have to enter a state of deep discharge to power the cooler for approximately 12 hours.

From the vaccine temperature graph (Appendix Q, Fig. 39), the temperature of the thermal masses used in the two respective 48-hour full-PV system tests were significantly different at the start of the tests (i.e., approximately 6 °C for the first 48-hour test and -6 °C for the second 48-hour test). For the second 48-hour PV system test, the plateau of the curve after the first 12 hours of the test suggests that the thermal mass was stabilizing the temperature of the vaccine vials. The temperature was maintained for approximately 6 hours. After 12:00 AM the next day, the temperature in the cooler reached the maximum vaccine vial storage temperature and began functioning solely under battery power. Even when the DC power supply began its second ON cycle, the battery did not have enough current to supply the load nor did it have the sufficient to time recharge. Thus, the cooler eventually stopped functioning at approximately 6:00 AM the next day. During both tests, the cooler ceased to receive adequate power after the end of the last DC power supply cycle. In both cases, the rate at which cooler temperature began to increase after the battery and load units had shut down was consistent. These findings were also consistent with the LTspice and MATLAB analysis which suggest that the battery would be unable to fully recover from deep-discharge in both of the 48-hour full system tests. The team inferred with a high degree of certainty that the lack of load current, when the DC SAS power supply simulated the second daytime condition, was due to the low PV power input (i.e., using a single 100-watt solar panel) and low charge controller current allocation for the battery.

D. Constraints

There were multiple constraints on the ideal design for the SPVR system that limited the scope of the project. One of the most notable constraints on this project was the limited access to funds. The team applied for the OIT Resource Budget Commission (RBC) Proposal fund in November 2019 but were not granted any funds to help with the purchase of materials. Thus, the project was largely funded out-of-pocket ($44.35) and from access to the consumable fees associated with OIT student project fees ($120). For this reason, a limited prototype SPVR unit was agreed upon. Additional help was provided by Richard Ellis (OIT Instrument Technologist 1) who donated and gave the team access to several critical components to make a functional prototype. He also provided the team with access to testing equipment to evaluate the performance of this unit.

The design of the system focused on portability and cost effectiveness which limited the size of the system. Since this project focused on transportation and cost effectiveness, a short time of operation was chosen. Under ideal operating conditions, the cooler would have to be placed indoors due to the variable climate in Uttar Pradesh. For these reasons, four hours of operation was chosen as the ideal time of operation. This reduction in sizing also limited the project's ability to support a secondary load (i.e., cell phone charger) since refrigeration was the main component with a high-power draw. In addition, the equidistant spacing between vaccine vials (i.e., in accordance with the WHO guidelines for vaccine storage) was not possible due to material availability, time availability, and economic constraints on this project. Thus, the team chose to follow the CDC guidelines for vaccine transport in emergency situations which did not have a specified vaccine vial spacing requirement [12].

Uttar Pradesh was chosen in part due to the abundance of information that was present about the climate and weather in the area. Allahabad is a large city located in the state with an adequate amount of data in terms of solar irradiance, weather patterns, and cloud cover. Other constraints included the difference in climate between Portland and Allahabad which prevented the team from completely matching the conditions of the target location; the low and highly variable amount of solar radiation & weather conditions in Oregon (i.e., which required the use of DC variable power supply to provide constancy in all power measurements); and the limited time for project testing that forced the team to choose only primary parameters directly relevant to vaccine refrigeration for measurement. Minor sensitivity analyses were briefly considered and placed in future areas of study.

E. Possible Risks and Complications

For this project, the team analyzed the hypothetical scenario where an SPVR unit with similar capabilities was implemented in rural areas of Uttar Pradesh, India. In this scenario, the initial parts of the SPVR unit would be sourced from the most cost-effective retailers in India or China. The unit would be assembled in the United States by all team members and transported with the necessary building accessories to Allahabad. All four team members would be responsible for contacting the community health center or cold-chain transport center to coordinate the vaccine transfer (i.e., for a trial run of this technology). We would also be responsible for setting up the units, performing a one-day temperature test, and including as much as 40 (25 ml) vaccine vials for Hepatitis B and Polio for transport to a single rural destination. We would remain with the medical transport personnel for approximately 2-3 weeks to provide necessary technical support and guidance for self-operation of the unit. We would also verify and record the performance of the system during that time through physical checks and audio conferencing in accordance with CDC regulations. After the system had been tested for a set period, we would return to the United States and develop a full report of the team's findings while maintaining contact with the medical staff using this technology.

In a hypothetical operation of this scale, there will probably be various underlying political, economic, and environmental scenarios which will be associated with the implementation of this project. Each challenge comes with some degree of inherent risk. These risks may include, but are not limited to:

- Construction Risks - originating from damage or safety risks stemming from improper electrical or physical setup errors
- Team and Institution Risks – relating to errors in communication and the logistics of implementing the technology in the desired region of Allahabad
- Weather-related Risks – relating to unpredictable natural disasters that may delay this project or even damage the equipment setup
- Financial Risks – sudden changes or cancellations in the funding of this project
- Operational Risks – reduction in manpower, technology, equipment, and logistics due to unexpected reallocation of resources (e.g. national emergencies, war, or pandemics)
- Regulatory Risks – relating to changes in governmental or local policies on the implementation of solar-powered medical technologies in rural areas
- Damage Liabilities and Risks – criminal activities that could impact the successful construction and operation of this project (e.g. theft and sabotage of equipment)

If these risks materialize, they could possibly complicate the implementation of this project. Some of the complications include, but are not limited to:

- Finding alternate equipment and material sources that could provide replacement technology at a fast delivery rate (i.e., higher cost involved)
- Creating special error correction procedures for improper unit configuration scenarios
- Finding suitable facilities in underdeveloped regions of Uttar Pradesh that could support construction and testing of equipment over long periods of inclement weather

- Finding alternate sources of funding or loan agencies with a low interest rate
- Contacting other community health agencies and technology companies who have a vested investment in their industry to serve as alternate sources of help for implementing this project in Uttar Pradesh during a crisis
- Reviewing policies and legal documents regarding legacy support for previous foreign-based outreach community projects for renewable energy (i.e., in the scenario that regulations become more stringent on solar technologies). This may involve hiring a special legal assistant or lawyer to support the team's case.
- Maintaining connections with law enforcement and community members to seek those responsible for equipment damage and to contact local technology companies for immediate replacement of parts (i.e., which may incur a higher cost)

A special risk management team or hired firm would be beneficial to effectively anticipate and prepare for these challenges and risks, as well as help expedite the implementation of this project with minimal interruptions.

F. Technology Maintenance and Lifecycle

The PV system will require routine inspection and cleaning. Solar panels will need to be checked for any dust or debris every 2-3 weeks to avoid hot spots. Charge controllers will also need to be checked daily for any overload warning signs. The charge on the batteries must be monitored daily to evaluate days of autonomy in case of weather changes.

The PV panels have a life expectancy of 25 years, and most other essential components have a life expectancy of 20 years. If the components last up to their nominal life expectancies, the SPVR system could be anticipated to function with minimal maintenance for 20 years.

According to a preliminary estimate acquired from UPS.com, costs for shipping one unit with a weight of 40 kg from Portland, Oregon to Allahabad, Uttar Pradesh would cost 888 USD. Whereas this price is not economically viable, there would likely be a reduction in cost per unit for bulk shipments.

The lifecycle of the PV system is generally dependent on the performance warranties of the individual components. In the optimal case, solar panels have 25-year warranties, batteries have 10 to 15-year warranties, and charge controllers have 5 to 10-year warranties.

With any system using a compressor (Appendix H), there is the possibility of occasional maintenance that may need to be performed on the compressor. Compressors are commonplace systems with which technicians worldwide should be familiar; therefore, any required service should be attainable at a reasonable price. The average lifespan of a compressor for a compact refrigerator design is between 10 and 14 years.

If all components last for their entire lifecycle, the annual cost of the system, including initial shipment costs, would be 125 USD. This does not include the cost of any incidental maintenance that may be required of the mechanical or electrical components of the system. However, this is the ideal case and it is probable that some mechanical or electrical failures could occur. Equation (3) was used to determine the costs of system maintenance over a period of 20 years and considers all materials that would have a lower probability of lasting through their anticipated lifespans (i.e., due to mishandling, accidents, or excessive wear and tear) [18][19]. Based on (3), the estimated cost of replacement parts would be $515.69 over a period of 20 years (i.e., ($237.99*10/20) + ($539.00*14/20) + ($193.99*2/20)).

$$\text{Estimated Cost of Replacement over a 20-Year Period} = \text{Sum of Component Costs} * \text{Actual Lifespan} / 20 \text{ years} \tag{3}$$

G. Benefits to the End-Consumers

One of the upfront benefits of this technology include reliable delivery of potent vaccinations, thereby reducing the incidence of polio and other epidemic viruses that affect Uttar Pradesh. This creates more healthy, able-bodied members of society that can contribute to their community, whether at the regional or international level. With more capable components, the system could likely power secondary loads such as mobile phones and other small electronics. Once the system has reached its destination, the design of this system could allow for people to charge their mobile phones and small electronic devices for a small fee, allowing for the generation of capital, and a return on investment that helps community members. The secondary benefits include a reduction in reliance on grid-based systems that utilize fossil fuels and increase carbon emissions.

H. Transportation Requirements

The movement of vaccines between medical facilities would require an efficient means of transport of the cooling unit. The largest component in the SPVR unit is the PV module which would have to be stored in a separate cargo bag or container during transport. The battery, cooler, and charge controller could be placed in a separate container. The main limitation is the ability of the battery unit to recharge during long-distance travel. Unless the vehicle has the capacity to hold the panels (on the roof) and connect to the charge control system, charging during travel will not be feasible.

I. Site Assessment

The desired location for the SPVR project is Allahabad, Uttar Pradesh, India. Uttar Pradesh is home to a population of 199.8 million that are underserved in access to medical vaccines [20]. Since Uttar Pradesh is located along the southern foothills of the Himalayan Mountains, one of the difficulties in distributing vaccines in this region is how mountainous the terrain can be and the relative distance between large sections of the population. As reported by the National Family Health Survey, 68% of the population has received the full dosage of the Polio vaccine which leaves approximately 60 million

people who are not properly vaccinated [20]. This makes Uttar Pradesh one of the least covered states in India for vaccination inoculation for the general public. This led the team to choose this location as the proposed application of the SPVR unit.

Many refrigeration units are only able to lower their internal temperature to a certain temperature below the ambient temperature. Uttar Pradesh is a very warm state, which was a significant limiting factor on the working conditions of the SPVR unit design. Since the operational period for the SPVR unit is limited to the winter months (December – February), optimal sun hours for the area are also limited due to the natural reduction of solar hours during winter months. This effect is not as prominent as it is in other northern hemisphere locations due to Uttar Pradesh's proximity to the equator, but it does factor into the system sizing. The solar irradiance for Allahabad, Uttar Pradesh for the winter months is shown below [21]:

- December: 3.31 kWh / m^2 / day
- January: 3.35 kWh / m^2 / day
- February: 4.43 kWh / m^2 / day

Depending on the terrain in Uttar Pradesh, it may prove imprudent to wheel the Igloo cooler. If the ground is very rocky, wheeling the cooler could result in damage to the vaccine vials.

IV. Economic Feasibility of the Proposed Technology

The following sections will cover an in-depth economic analysis of the hypothetical scenario where this technology is delivered to an underdeveloped country who will bear the initial and long-term maintenance costs of the system.

A. Microeconomic Analysis

To add to the existing hypothetical scenario, we consider the economic effect of this technology to the market within a given underdeveloped country. The main assumption is that all underdeveloped countries have similar needs in terms of food, shelter, water, and an adequate living environment. In this analysis, we assume that all market participants act rationally in their own self-interest without changing their preferences [18]. They also maximize the quantifiable utility of their equipment and have equal access to information. In addition, governing organizations also act as individual participants. There are also no barriers to entry in the PV market with minimal externalities that affect competition [18]. The market is represented as an aggregate collection of decisions made by individuals.

There are currently a wide range of solar-powered refrigerators available in the Indian market from retailers such as IndiaMART, Bharat Solar Energy, and Meditech Technologies India Pvt. Ltd [22][23][24]. There are also international wholesalers such as Alibaba that provide this technology specifically for users in India. While some of these technologies may not necessarily meet the needs of the medical industry applications such as vaccine refrigeration, this highlights the growing demand for this technology because of its high reliability, efficiency, portability, and decreasing costs [25]. This also indicates the efforts of national and local policymakers to reduce barriers to entry, eliminate monopolies, and externalities that are symptoms of market failure [18].

With all economic factors held constant, the high prices of standalone PV vaccine refrigerators match the relatively large supply of this technology within India which is consistent with the law of supply [18][25]. If we consider external factors such as demand location and consumer preferences, the introduction of a small-sized PV vaccine fridge unit in Uttar Pradesh would increase demand for this type of technology and serve as an impetus to develop and support the purchase of larger-scale PV vaccine refrigerators for health subcenters and community health centers in Uttar Pradesh.

The Pareto optimality seems to be reflected in medical facilities around India. Hospitals in India are currently cutting costs by focusing all expensive technologies in high volume areas and more rudimentary technologies in small villages [18][26]. This suggests a high supply of expensive equipment, but low demand due to the costs of production. The introduction of low-cost or donated PV vaccine refrigeration technologies would increase development and aid vaccine relief efforts. This technology could be combined with other fundraising or business initiatives such as co-use of PV vaccine technologies for basic amenities (e.g. cell phone/small tablet charging) at a nominal fee to customers. This could serve as the means to fund medical facility expansions or to acquire more expensive technologies where it is most needed in areas of Uttar Pradesh. As the cost of materials to build PV vaccine cooling systems decreases, the cost of these systems for end-consumers should also decrease because of reductions in the costs of the factors of production (i.e., land, labor, and capital) required to develop these technologies. Ultimately this makes such systems more affordable for many community health subcenters, thereby increasing demand and leading to market equilibrium [18].

Some of the factors affecting short-term supply of the team's SPVR system include material and production costs; prices of similar renewable vaccine cooling methods; changes to price productions; policy restrictions; and the number of suppliers in the market [18]. Some of the other factors that would affect demand for this system would be the price of substitutes & compliments to this technology; changes to the predicted technology prices; changes in the income or preference of the end-consumer [18][27]. The social benefit for this system would be the sum of end-consumer and external benefits [18][28]. Some benefits for the end consumer would include savings on purchasing commercial grade vaccine cooling systems; low maintenance costs; and utility of the technology. External benefits could include decreased pollution from using PV systems instead of diesel generators to power the refrigerator and decreased medical costs for vaccine patients. The price elasticity of demand for PV technologies has been relatively elastic due to competition between several power sources (i.e., grid at -0.74, diesel at -1.34, off-grid solar at -3.48, and microgrid solar technology options at -2.34) according to the report "Demand for Electricity in a Poor Economy" by

Burgess et. Al [29]. The major factors that can affect price elasticity of demand include substitutes, necessities, time, and consumer habits. The report states that:

> *the finding of high elasticity implies that anticipated innovation in solar technology and small changes in government policy, which in turn affect the characteristics of different electricity sources, may have dramatic effects on the electricity market. These are explored in our counterfactual analysis. We find that further reductions in solar prices would moderately increase its market share, mostly arising from adoption by households that would not otherwise be electrified. However, when solar is the only electricity source available, its market share is limited to 34% and almost two thirds of households choose to remain in darkness. Indeed, willingness to pay for off-grid solar is considerably lower if the grid is available, so that it appears to be more of a stop gap – albeit a potentially important one – for households who do not have access to grid or for poor households who cannot afford full-cost grid electricity. In this sense, solar power is valuable in large part because the grid is incomplete and dysfunctional* [32].

B. Macroeconomic Analysis

Adding to the existing hypothetical scenario, we consider the economic effect of this technology to the national marketplace of India and the potential effects of this technology on the entire country. The assumption here is that this product is manufactured and distributed in India.

Increased human capital improvements, capital investments, labor force growth (through population increases), and improvement in technology have contributed significantly to India's expanding production possibility frontier in the PV related technologies such as vaccine refrigeration [29][30]. The production possibility frontier is a defined set of choices people face for any combination of goods that can be productively efficient. If more of one good is produced, then the production of another good will be reduced.

Some of the factors that affect aggregate demand for these technologies include total consumption, investment, government spending and net exports of materials. In particular, per capita income increases have been significant drivers of consumption changes with the per capita NNP increasing by 1000 crore every 3 decades [31]. This is one indication that PV cooling systems will eventually become more acquirable for individuals and owners of small health facilities. Government policy and support for investment in solar technology has resulted in the creation of 23,499, in aggregate, capacity increases as of March 2019 [32]. This data may suggest that technological changes and production processes have become efficient to the point where large-scale projects would be cost-effective and feasible. In this case, if this trend continues, the mass production of the team's small-scale solar-powered vaccine units could become a critical factor in expanding solar-powered medical applications to rural areas thereby reducing electricity costs, especially for health subcenters and community health centers in Uttar Pradesh.

Charles Ebinger of the Brooking's Institute highlights two major issues that India faces in terms of energy policies and production of electric power. He mentions that:

> *the most serious issue India must address is that the gap between energy demand and energy supply is wide and growing. Two reasons for this trend are demographics and economics: not only is India's economy growing, thereby demanding more energy and electricity, but the population is as well. There is also massive urbanization, which is putting more pressure on energy and the environment* [33].

He also highlights climate and geographical challenges for the transmission of power, mentioning that:

> *India's power network comprises five regions spanning the country. While each is connected to a neighboring region, there are inadequate interregional connections through high voltage transmission lines, creating difficulties for moving power from electricity surplus states to those in deficit. This also creates difficulties on a seasonal basis, as power is often in short supply during the dry season and abundant in some regions during the monsoon but cannot be moved to help other states. An additional complication is that India's investment in power transmission and distribution has not kept up with generation. Thus, in some cases, new generation cannot move to the market because of transmission bottlenecks, such as with wind power in Tamil Nadu* [33].

In terms of energy policy, "the land acquisition bill is under debate in India. This bill must be comprehensive and fair to both owners and purchasers. Most importantly, however, it must be transparent and enforceable. While India's energy sector is improving, the biggest problem for investors is that translucent regulations and processes drive up private sector costs. A clear and egalitarian bill can accelerate projects in the national interest while providing fair compensation for those displaced" [34]. While these issues remain to be addressed, this technology would provide the necessary services to provide immediate relief will developing the medical sector to meet future demand increases for services such as vaccination. The increase in solar technology availability and the diversification of applications suggests that aggregate supply for PV powered vaccine refrigeration will be relatively elastic in the long run. Significant changes in LRAS (long-run aggregate supply) can be influenced by a variety of factors such as income or wage reductions, deregulation of the solar industry, privatization of industries specializing in vaccine cooling technologies, research & development, physical/informational infrastructure development as well as improved education of the labor sector [31].

There is also the difficult question of the 'value' of a human life [31]. How would one quantify the monetary value of one human life that is taken by improperly stored vaccines or the

lack of ability to safely transport vaccines to people in need? There are several methods that have been put forth and one of the most relevant method seems to be subtracting the value of PV technology output across the economy from the value of intermediate consumption [31].

India's current inflation rate stands at 3.6% (CPI), which is relatively low compared to other nations with an equally sized economy [35][36][37]. This could potentially mean that the rise in prices of technologies in the long-term will also be gradual and purchasing power of money will remain stable. However, one of the driving concerns is the high interest rates which have the potential to reduce overall investment activity in industries such as PV and cooling systems. In terms of the unemployment rate, India is nearly comparable to developed nations in the G20 with a rate of 8.50 percent as of October 2019. Their youth unemployment rate is 23% [36]. This statistic does not cover underage workers and mutually accepted underage workers which are a significant part of the workforce (33 million), but do not appear on any official government census in India. Some of the highest figures come particularly from Uttar Pradesh [38]. Considering that this type of labor system is integral to India's economy, the mass application of this PV technology would employ more workers in the manual production and installation sectors of the economy. Higher vaccine transportation rates would also increase employment in the transportation sector and help attract more money to working class families in need.

When hiring a labor force with workers of different skill sets there is also the issue of how to address workers with knowledge that has been rendered obsolete by the fast-paced PV industry [34]. In this case, more costs would be incurred through training, but would be recovered by the increase in worker productivity (i.e., PV vaccine cooling system production) and higher profits. Direct and indirect government taxation of PV technologies used to provide services, reduce negative externalities associated with consumption of goods, and protectionism. Considering that India is a lead exporter of vaccines and a notable retailer in cooling systems, they have a relatively low level of protectionism for these types of products [39].

Equitable distribution of income would also be a beneficial byproduct of the introduction of this technology. Several government actions that could be taken include graduated taxation, merit goods subsidizing, and payment transfer services [34]. Subsidizing the production and distribution of this technology in Uttar Pradesh would serve as a platform for creating new jobs, reducing expenditures, and benefiting the health of rural communities. Healthier communities will have more potential to serve India's growing technology sector thereby increasing economic expansion and balancing income distribution.

C. Effect of Energy Policy and Regulations

Energy policy attempts to address four main concerns: energy security, reductions in toxic emissions, economic development, and equity & accessibility for the energy industry [35]. According to an official SAGE report entitled "India's Energy Security: Critical Considerations" by Arora et. al., India relies mostly on domestic and foreign coal and oil, which are vulnerable due to internal and international conflicts that could compromise the supply of these resources [36]. The increased use of PV technologies in critical sectors such as the medical industry could increase energy independence thereby increasing energy security. A change to renewable energy would also improve economic development through the creation of additional jobs, as more industrial workers will be needed to build and install solar panels. However, these changes come at a heavy cost, especially for industries that must restructure their systems, as well as special land acquisitions by the government for solar panels (or solar recharging areas). Considering that India has shifted to a market economy, most of the costs would be placed on the people and partially on businesses [37]. The benefits of this change would be minimal for well-developed communities and cities but would be especially evident in more populated areas of India with limited access to power or a heavily constrained power network.

India has been one of the world's largest contributors to global air pollution for the past several decades [38][39]. Their government has recently set targets to reducing industrial and vehicular air pollution as of 2017 through the National Clean Air Program (NCAP) but has not revealed specific information on their approach [38][39]. Most of the economic burdens imposed by excessive emissions come from long-term health issues related to smog; negative impacts on drinking water; losses in tourism; fishing & shellfish harvesting industries; and reductions in the value of real estate [38][39][40]. The mass manufacture and implementation of this system could serve as a small but significant step towards the net reduction of polluting energy sources such as coal, oil, and other fossil fuels. Both the public and businesses bear the costs & benefits of emission reductions programs. The net return on investment would be significant considering the improvement in seafood, tourism, and energy industries [41][42][43]. Equitable access to electricity from renewable sources is both an economic cost and benefit. For people and business to have an equal share of renewable energy benefits, priorities must be set regarding the nature of the energy need and the location. Safety needs (e.g. emergency relief efforts) are the highest priority, while health needs such as vaccination of children are nearly equal in importance. Thus, the team's standalone PV vaccine refrigeration system comes as an important addition that could relieve energy demand burden on existing renewable systems and provide necessary time for development of both the medical sector (i.e., gaining money to acquire more superior technologies) and the energy sector (i.e., to develop more high-output renewable energy generation systems). India appears to have made renewable energy as one of its policy goals – supporting the planned development of 175 GW of renewable capacity by 2022 according to the National Renewable Energy Laboratory [41]. Several options are open to policy makers to achieve this goal which include subsidizing energy through tax credits & feed in tariffs; subsiding energy prices or capacity

expansion through corporate investment or loans; or subsidizing the manufacture of renewable energy systems through direct funds (from taxes) on hardware or the acquisition of hardware from other countries [42]. The choice of what or how many areas should be subsidized is dependent on the economic situation and the public's willingness to pay for a future benefit. Ideally, equal subsidies or subsidies that favor more efficient technologies would be a good initial platform. As mentioned previously, these subsidies depend on consumer & business taxes and fees [42]. From the consumer perspective, a shift to renewable energy does not constitute any tangible savings, but it does promote long-term energy security and a reduction in pollution.

When considering the implementation of any renewable energy system, the concept of negative externalities must also be considered [42]. There are hidden aspects of costs which could affect those who do not benefit (e.g. plants and animals) as well as those who pay the upfront financial costs of a venture but not the public costs (such as pollution and noise) [42]. Solar panels do not have any emissions, but solar production companies may still depend on fossil-based energy sources, and the toxic fumes emitted during production collectively contribute to a significant amount of carbon emissions [43]. However, the net long-term benefit is pollution reduction assuming that solar PV systems last their full lifecycle (i.e., approximately 20-25 years). One solution to help encourage the shift to having renewable energy sources power critical safety and health-related services could be emissions taxes. On the other hand, some industries may engage in efficiency improvements, but not necessarily make system-wide energy source changes due to the nature of their business (e.g. transportation and large oil industries).

D. *Multi-Objective Economic Decision Process*

In an ideal case where the team was successfully able to implement this solar vaccine technology in Uttar Pradesh, there will always be a single optimal outcome that results from acting upon any decision that the team decides to make. However, to make the situation more realistic, multiple factors and options must be involved which complexify the problem [44]. In order to arrive at a possible solution, a trade-off analysis that considers all criteria of the problem would be needed to understand the priorities of the different parties involved in a decision-making process [44].

The decision-making process always involves multiple objectives which is subject to constraints (i.e., rules or limitations). The extent of these constraints depends on the decision variables [44]. This report will focus on one multi-objective decision-making approach to implementing a PV vaccine cooling system in Uttar Pradesh, India. There are seven major steps outlined below.

1) Identify all the relevant stakeholders
2) Identify all the relevant objectives and attempt to quantify them
3) Variables and Constraints must be defined
4) Data must be collected to gain understanding of the problem
5) Alternative decisions must be developed and evaluated
6) Non-inferior alternatives must be selected from the group of alternative decisions
7) Select and implement an alternative decision.

This process repeats with the goal of finding more optimal solutions for complex problems. For this project, we will briefly consider three categories of stakeholders – primary stakeholders (i.e., directly affected parties by the implementation of a decision); secondary stakeholders (i.e., parties that are indirectly affected by a decision); and key stakeholders (i.e., individuals or groups that have the potential of positively or negatively impacting the implementation of system) [44]. In this case, the primary stakeholders would be children and young adults that are at risk of vaccine preventable diseases which are widespread in certain parts of Uttar Pradesh. Secondary stake holders could include family members, friends, and other people that could be affected by communicable vaccine-preventable diseases. Key stakeholders could include policy makers that permit the development and implementation of national and foreign renewable technologies that benefit the medical industry. In addition, community organizations such as health groups, churches, and schools could all serve and sponsors of this project.

The objectives for this project include developing a PV-powered vaccine refrigeration system with the ability to charge secondary loads (if necessary). In this hypothetical scenario, we also plan to implement this system in Uttar Pradesh, India. The development and implementation of this system must be low construction, maintenance, travel, and replacement costs with long lifespan (for good return on investment).

The variables for this project include fuel prices for the transport of material, climate conditions, power outages, availability of labor, conflicts in the target location, and the price of raw materials. The constraints for this project include the rules set forth by supporting institutions (i.e., OIT), availability (or lack) of funds for the project, transportation requirements, government policy restrictions on equipment used to medical care in India, as well as time to implement the project.

Data collection for this project will consist of analyzing the yearly climate conditions of Uttar Pradesh; temperature and time relationship for compressor-based refrigeration; total power consumption during different times of year; prices of transportation fuel and travel fees; and the quantification of government support (or restriction) on the implementation of renewable powered medical equipment in rural provinces of India (i.e., in terms of government funding).

One of the major sources of uncertainty and concern for the team regarding project design, development, and construction is project funding. Thus, the team created several tiers of materials lists based on the amount of funding we would be able to obtain from the Resource Budget Commission of OIT (refer to Appendix F). We also evaluated the priorities of this project and the desired knowledge and skill sets we plan to acquire from this experience. This was used as the basis to

decide what should be done if no funds could be acquired. Below is a summary of the alternatives:

1) Full Funding: High power PV system (100 Watt) with oversized battery (i.e., to handle secondary loads) and self-powered vaccine fridge system. The system comes with accessories for component and load protection and tools for system maintenance and adaptability to different connection systems. In addition, it includes system test equipment and a cell phone for communication. This system would cost approximately $2,600 (based on tier 4 of the RBC proposal calculations – Appendix F).
2) Partial Funding: High power PV system (100 Watt) with oversized battery (i.e., to handle secondary loads) and self-powered vaccine fridge system. The main accessories and protection elements for the system to run are included. This system would cost approximately $980 - $1,300 (based on tier 2 and 3 of the RBC proposal calculations).
3) No Funding (Out-of-pocket Expense): Medium power PV system (100 W) and small-sized battery (i.e., enough to meet short-term cooling applications) with a low-cost, low power mini-fridge. This would involve donated materials from the PV lab and power labs of Oregon Institute of Technology. This system would serve as a testable prototype that could be used as the basis for a larger, more robust system. This system would cost about $44.35 (based on the actual selected non-consumable and consumable project materials for this project).

From the hypothetical sense where we implement this technology in Uttar Pradesh, there are several alternatives that the team could consider. Here we will assume that we will be testing and evaluating the success of a single PV vaccine cooling system in the cold chain to determine whether more units could be produced and implemented. Options 1-3 below apply to options 1 and 2 for the PV systems above.

1) Single Year-Round Mobile Application: This would cover transportation, on-site maintenance, replacement, and labor costs for having students installing, tracking, and checking the system to obtain field data every month. Considering that the average ticket price per person is $1,645 (round trip with a stay of 1 week in Uttar Pradesh); cost-effective hotel rates of $70 per night (based on TripAdvisor); assumed key component replacement costs of $300; van rental at $54 per day (according to kayak.com rates); and food costs of approximately $29 a day (based on Budget Your Trip); and four group members to help with implementation; the total cost could be approximately $10,030 per month and $120,360 for 1 year (i.e., with monthly visits to this system) [45]-[49].
2) Scheduled Mobile Application: Our system could operate for 2-months during the cooler winter season, and for 2-months during peak heat to understand any hardware improvements that need to be made. This would cover transportation, maintenance, replacement, and labor costs for having students installing, tracking, and checking the system to obtain field data every month. Based on the rough calculation for implementation costs (above), the total expenditure could be at $40,120 (assuming a 4-month checking period) [45]-[49].
3) Remote, Guided Application: A mobile health facility can be contacted to receive and test this system with specific instructions on system assembly and maintenance. We can request the facility to provide specific data on how this system operates and possible improvements that could be made to suit their region of operation. Considering shipping costs of approximately $500 (for 2-5 shipping for a single 100-lb package, based on myus.com) and administrative costs assumed to be $55 per hour (based on annual salaries for family medical workers in India and assuming a 8-hour workday), the total costs for a 12-month system implementation and evaluation would be $20,500. This cost assumes that the staff in Uttar Pradesh are paid to make brief checks on the system for a total of one hour of work on the system per day for one year [50][51].
4) Remote, Guided Application for Prototype: Similar to option 3 above, the total costs for this lighter system (approx. 30 lbs), would be $20,270 (with a shipping cost of approximately $194 for 2- to 5-day shipping) [50][51].

The system and implementation costs have been calculated and estimated based on item, equipment, and other implementation costs as of January 4, 2019. When selecting optimal alternatives from the lists above, all significant factors such as technology development time and available funds must be considered. Since this project was not selected for funding from the Resource Budget Commission in December 2019, option 4 for the PV system and hypothetical implementation would be the most suitable choice. Considering that we had received funding for this project, the following question arises: how much would we be willing to pay for additional system features and implementation options? This decision would be heavily dependent on Oregon Tech engineering department funds and less on out-of-pocket expenses [44].

All options presented in this section are means to other means. For instance, developing a prototype of the team's PV vaccine cooling system would be a means to improving this system and customizing it to the cold chain system in Uttar Pradesh. That would also be a means to finding solutions to mass manufacture and implement this system over a wider region with the ultimate goal of being able to provide reliable, cost-effective, and low-maintenance vaccine cold-chain technologies to rural communities in underdeveloped countries around the world. Each alternative course of action is equally useful in determining the next step to achieve the team's goal (i.e., there are no inferior solutions). One objective such as cost may have been optimized while all other objectives were set as constraints [52].

One of the biggest advantages of the SPVR system is the small land use and negligible environmental impact that would be incurred during the use of this system. However, one of the significant concerns that impacts the energy industry

is the recyclability and disposal of batteries and other PV materials which contain toxic chemicals or gases that can damage the environment when degrading. Further research will be needed to understand India's policies on renewable energy system waste disposal (at the end of the lifecycle of certain components).

When implementing this system at a large scale, there is also the question about how the large-scale expansion of this technology in the medical sector could possibly impact global poverty and income distribution. Our technology focuses on maintaining the quality and potency of vaccines which is a crucial factor that indirectly affects the quality of healthcare in India. Improvements in this sector allow more children to be protected from vaccine preventable diseases and contribute more effectively to the workforce of India once they reach the legal working age. This system also has the potential to create new industrial and commercial jobs pertaining to the manufacture, sale, and implementation of PV vaccine cooling systems which can help lead to better income distribution and reduce poverty (i.e., for those who do not have jobs). Further advancements in PV technology as well as the increased production of this technology can lower prices across the market making this system more affordable in the long run [53].

E. Project Cost Estimates

The following table shown in Appendix G include a tentative list of materials, equipment and associated prices based on the most optimal cost-effective options on the market that have been researched as of February 20th, 2020. The total out-of-pocket expenses for non-consumable materials was currently at \$44.35. The PV trainer which includes the DC Simulated Solar Array Power Supply, DC Load Simulator, charge controller, 10-way fusebox, and DC circuit breaker has a total combined worth of approximately \$8,733.53. The total consumable costs which were funded by the FEGP (Student Capstone Fees) amounted to \$106.

F. Marketability and Economic Impact Evaluation

The potential for a solar powered vaccine refrigeration unit to be introduced into the market of a critically underdeveloped nation relies on several major factors which include retail price, return on consumer investment, long-term product reliability, and availability of source materials. In addition, some of the most successful PV projects and endeavors have resulted from the ability of individuals and businesses to engage in the resale of parts of the system or use the renewable technologies to generate income. Therefore, future upgrades to the current PV vaccine cooling system could feature a larger energy storage unit to service more loads (e.g. paid recharging of tablets and computers or the ability of low-cost cell phone communication powered by this PV system) [53][54].

Several significant leading and lagging economic indicators for a product-specific industry are applicable for PV vaccine cooling system. Some important leading indicators include the current stock market value, market-value of solar powered vaccine cooling technology, manufacturing activity (costs), value of inventory, value of distribution, building permits, and development of new related firms. Some of the lagging indicators may include effects to the GDP from RET firms, demand for jobs, and corporate profits. A detailed explanation on how these indicators would guide implementation and marketing plans could be discussed in future revisions of this project [55].

G. Cost-Benefit Analysis

Vaccine refrigeration units that rely on renewable technology could be built as a pre-designed unit or a modifiable unit with a "base" design. A pre-designed unit with fixed capabilities would be easier to build and manufacture which would lead to reduced production & end-consumer costs. Another aspect to consider is manufacturing. A simple, but robust modular unit design will allow for faster and cheaper mass production. If this product is to be assembled at several plants located within these developing countries, then the ability to satisfy consumer demand relies on availability and accessibility of raw materials. Thus, any endeavor would require careful consideration for the direct costs associated shipping and handling as well as satisfying the needs of a localized workforce.

In terms of finances, healthcare facilities will also be concerned about the monetary value (or worth of this system over time). Our team will evaluate the net present value of the system we plan to use for the project. The formula for net present value is shown in (4) [56]. In this formula *i* represents the return or discount rate, *t* represents the number of time periods.

$$NPV = \frac{CashFlow}{(1+i)^t} \tag{4}$$

Assuming that we will be incorporating the RNG-100 solar panel into this system and excluding the DC SAS Power Supply from the cost analysis, the total cost of the system with accessories would be approximately \$322.91. If we assume that the required return is 8% and implementation of this test equipment will be for 3 months, this equates to a net present value of (\$322.91)/((1+0.08)$^{0.25}$) = \$316.76. For this system to be economically viable, the net return on this unit must be greater than the annual worth *A*. This can be calculated by (5), where *P* represents initial cost:

$$A = P\frac{i(1+i)^t}{(1+i)^t - 1} \tag{5}$$

If we assume that the required return is 8% and implementation of the test equipment (excluding maintenance and labor costs) will be for 3 months every year for the next 4 years, this equates to an annual worth of (\$322.91)*((0.8(1+0.8)^1)/((1+0.8)^1-1))) = \$348.74. From this result, the team inferred that the CHC or MHC facility owners must find a service of revenue or fund that would be able to exceed the net costs of this system provide this amount of return on investment for each year of use.

H. Social Implications

There is also the need for an in-depth analysis of the cultures and traditions associated with the target consumers (i.e., hospitals and the parents of the newborn patients). One of the factors of successful production and distribution of a product is a well-planned dissemination of technological information that would be acceptable to communities and their workplaces. Any conflicts within the target within or near the target region must be considered (i.e., the India-Pakistan territorial conflict). In future revisions of this document, an in-depth explanation will be provided on several possible "cases" for implementation as well as successful examples that have been done by other teams or firms in the past.

I. Project Financing

There were three methods for project financing that were considered for this project. The first was through grants and institutional funds. Applications for these funds were mostly dependent upon the time available for the group to apply for these funds as well as the availability of funds. As of January 5, 2020, the group had applied for the Resource Budget Commission proposal funds and did not receive any funds.

The second option for the group was to obtain funding through consumable fees which originated from student project fees (i.e., in OIT tuition). Considering that there are four members who worked on this project for three terms, there was a total of $120 available ($10/member per term). A purchasing request for the SPVR battery was approved by OIT. This used $106 out of the $120 in available funds. The team also used the third option of sharing the out-of-pocket expenses associated with the purchase of the TEC sealing material, DC thermostat controller, and DC timer relay.

V. Conclusion

A. Summary and Reflection

Implementing a PV vaccine refrigeration system that has the capability to provide power to secondary loads was a central goal of this project. Despite the lack of funds, the team was able to develop non-inferior prototype options that would serve as a means to achieving the ultimate objective – to provide a mass manufacturable solar powered vaccine cooling system to support the cold chain infrastructure in Uttar Pradesh, India. The current version of the SPVR unit has significant limitations resulting from the use of a readily available one hundred-watt PV module due to economic restrictions. However, further development of the design and material choices could create a more robust system that is applicable to a wider range of developing areas with similar medical needs and climate conditions.

In terms of testing the SPVR unit, the primary basis for the 335 Wh supplied to the PV system during the second 48-hour PV system test was the NREL data for Allahabad for January as of 2020. This source did not specify whether it was the total solar radiation for the day or if this was the peak solar radiation achieved (over a given number of peak sun hours). There was no data provided on the hourly solar radiation for the target location. Furthermore, the team was unable to find detailed, reliable, and credible information regarding the number of peak sun hours in Allahabad in January within the time available for this project. The team was primarily interested in simulating a realistic PV curve showing the rise and fall of input power (i.e., diurnal solar conditions). However, the team was only able to find and use the total sun hours per day and the total daylight period as the basis of how the solar curve was manually programmed in the DC SAS Power Supply. When designing the solar curve for the second 48-hour test, the team made all attempts to balance the number of peak sun hours while attempting to simulate a PV curve that roughly approximated a realistic solar curve.

In retrospect, testing this system with different DC SAS parameters that assumed larger solar panels and battery modules would have given a wider range of data for the team to analyze and determine the optimal PV and storage combination. The main advantage of using a one hundred-watt PV panel was that the team found the minimum possible component requirements for an SPVR unit to potentially store vaccines within the acceptable range of 2-8 ºC for approximately 32 hours based on the second 48-hour full PV system and load test. In short, the tests and simulations illustrated that a one hundred-watt PV system could possibly work, albeit for limited time applications, in the cold-chain system.

The economic and technical feasibility analysis provided the team with a clearer idea of the importance of various factors such as policies, labor needs, and cost constraints when developing the design for this project. The most indicative information came from the experimental results of the second 48-hr test, which illustrated the ability of the one hundred-watt PV module to generate enough current to simultaneously power the load and recharge the battery for a very limited period of time. The team had considered performing additional analysis to substantiate and possibly improve the SPVR system based upon these findings. However, that was not possible due to OIT's appropriate safety measures during the COVID-19 situation. Ultimately, the experimental results serve as a good basis for achieving a greater understanding of the limitations of the SPVR system and what must be done to make this system more feasible for application Uttar Pradesh, India.

B. Areas of Future Research

Considering the numerous project constraints that the team faced over the course of this project, there are several pathways for future research that could enhance the stability and feasibility of the SPVR system in Uttar Pradesh, India. First, obtaining an in-depth analysis of India's solar radiation data, sun hours, and weather data for specific target areas within Uttar Pradesh would improve the quality of the test parameters and serve as a basis for potential system deployment in other areas of Uttar Pradesh, India. In this context, various governmental and scientific agencies would have to be directly consulted regarding this information.

Another area of future research could focus on the design and modeling of the SPVR system. A clear upgrade to this system would be the use of a higher rated PV module and a battery unit with a larger storage capacity. Economic constraints forced the team to work with a 100 W panel, leading to a deficiency in current for battery, even when testing under optimal solar conditions. In addition, the 55 amp-hour battery chosen for this project was the slightly below the minimum, calculated battery size requirement for one day of autonomy. Thus, the battery module was unable to provide enough current for the simulated night-time duration. Considering the limited time constraints, the team was able to produce a circuit design of the charge controller – a critical feature of all PV systems. However, we found many challenges attempting to customize the voltage and current output to match the characteristics of the ALLPOWERS charge controller. Additional research into the circuit layout and charge controller algorithm(s) of this device could result in a better prediction of system performance before undergoing any system tests. In terms of modeling, a more thorough approach to the physical aspects of designing this system could possibly aid other mechanical analysis of this system such as thermal and structural stress testing. Understanding these factors would allow this system to work in a variety of settings in Uttar Pradesh, India.

In addition, there could be more in-depth research regarding the selection of materials that were incorporated into the design of this project. Due to the lack of external funding sources, the team focused on obtaining materials from the REE department and searched for cost-effective retail options in the market. Seeking more avenues of funding in future expansions of this project would allow the team to obtain materials and components that have more optimal thermal, mechanical, and electrical characteristics. For instance, using a portable compressor-based fridge that could cool its contents to a specific temperature range without dependence on ambient temperature would have the potential to increase the annual duration that this system could be applied in Uttar Pradesh, India.

There are currently two methods of vaccine storage in the cold chain system – sustained cooling (using energy storage) and direct drive systems that purely rely on solar power. Considering that the goal is to provide relief and development for the rural medical sector of India, a system that operates for 24 hours is desirable. Thus, some form of energy storage would be needed to provide energy during periods of low solar insolation or night-time hours. Lithium iron phosphate batteries have a longer cycle life and could possibly serve as a future alternative to lead acid batteries in terms of power capacity and energy performance. However, the availability and cost of materials in Uttar Pradesh, India was a primary concern the team had to consider. Thus, further research into higher rated, marine deep-cycle lead acid batteries could provide more application-related power stability and extended longevity over standard SLA batteries. Larger loads may require multiple renewable inputs and large storage systems such as compressed air or pumped hydro [53][54][57]. Further considerations for safety such as adding a separate battery charger switching circuit; fusing between the battery and the charge controller; and timed load control would benefit the end-user over the duration of the product lifecycle. Appendix H has more information about a possible idealized system that has the potential to benefit the cold-chain system.

One other area of research could focus on materials testing. Due to time constraints, the team decided to focus on verifying system component operation before conducting full 24 or 48-hour full PV system tests. A more detailed characterization of the electrical and mechanical performance of each component would lead to a better understanding of how this system would need to be maintained during implementation in any future target locations.

Finally, the successful long-term functionality of this technology, its distribution, and effectiveness in mobile clinics or community health centers could possibly provide new avenues for technological and market expansions. As mentioned in the project technology description section, some possible improvements on the planned technology could include additional secondary loads such as lighting. More investments could be made to research more specific, yet common needs of developing communities. This may involve a detailed study on cost-effective components with longer functional lifespans (i.e., PV modules, charge controllers, battery units). For more detailed information about possible future project directions that could be pursued from this project please refer to Appendix S.

APPENDIX

Appendix A: LTSpice Model and Simulation Result for the SPVR system

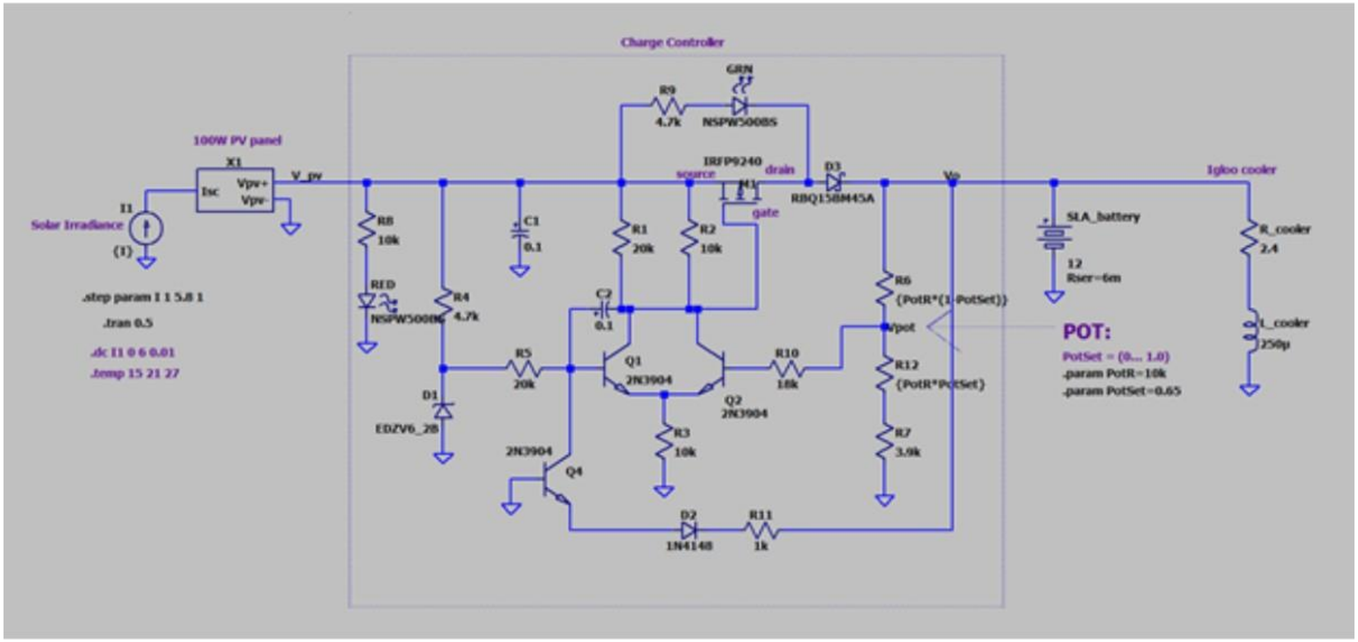

Fig. 4: Simplified model of the SPVR charge controller and its electrical connection to the rest of the system. Level of solar irradiation represented by variable current source.

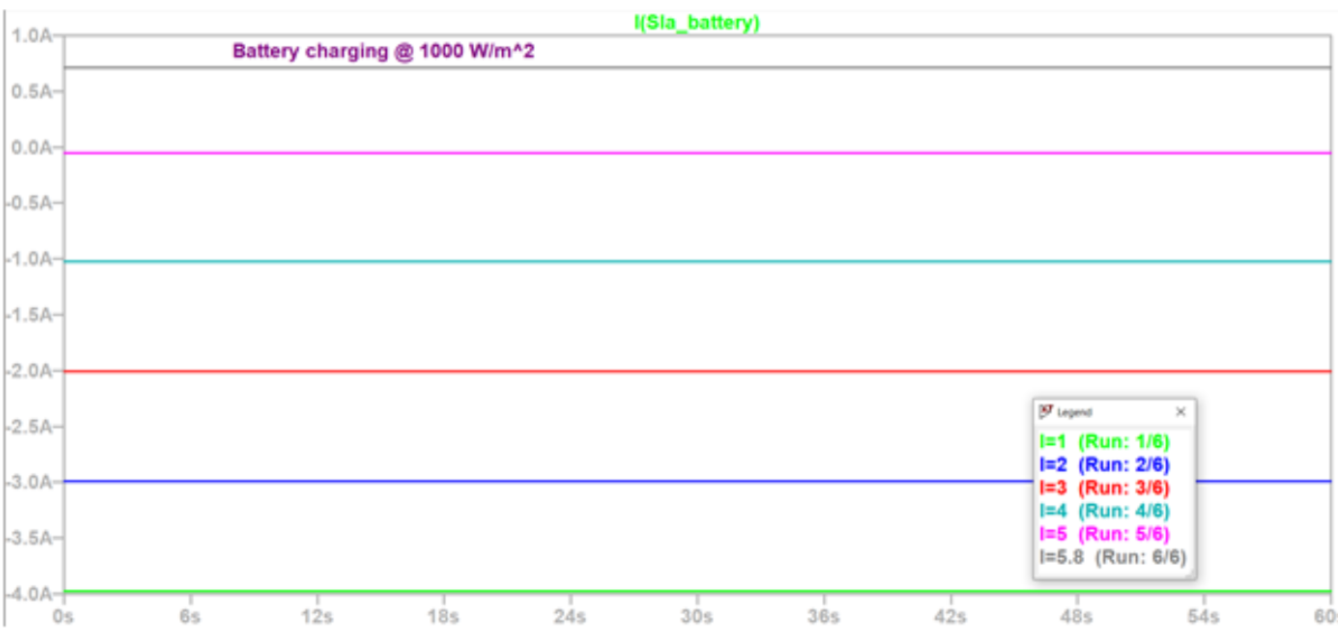

Fig. 5: Current through the SLA battery over a range of input values. The highest value represents solar condition during peak sun hour conditions in Uttar Pradesh, India.

Appendix B: Calculation Tables for PV System Sizing

The calculation tables below show how the PV system sizing was determined. Please note that the numbers colored in blue represent the input values and the red colored numbers represent the calculated values. The numbers in black are calculated numbers originating from a previous table in the spreadsheet.

TABLE I: Power requirements of the Igloo Cooler and the Temperature Sensor. The power demand of the load is used as the basis for sizing the PV panels and the battery unit.

Load Sizing Worksheet										
INDIVIDUAL LOADS	Qty * Volts * Amps = Watts * Use * Use / 7 = Watt Hours									
	Qty	Volts	Amps	DC	AC	Hours/day	Days/Week	Week Ave.	Wkly. Ave. Load (Wh)	
Igloo Cooler (28-Quart)	1	12	4.8	Yes		10.25	7	7	4132.8	
Temperature Sensor	1	12	0.25	Yes		10.25	7	7	215.25	
Total AC Watts:	0			Average AC Daily Load (Wh):			0			
Total DC Watts:	60.6			Average DC Daily Load (Wh):			621.15			

TABLE II: Battery sizing calculations for the SPVR system. The results indicate that it would take approx. one, 55 Ah, 12 V battery unit to have a system autonomy of one day.

Battery Sizing Worksheet				
((AC Avg Daily Load / Inverter efficiency) + Dc Avg Daily Load)/ Dc System Voltage) = Avg Amp-hour / Dday				
AC Avg Daily Load	Inverter Efficiency	DC Average Daily Load (Wh)	DC System Voltage	Avg Amp-hour/day
0	0.9	621.15	12	51.76
(Avg Ah / Day) * (Days of Autonomy) / Discharge Limit / Battery Ah Capacity = Batteries in Parallel				
Avg Ah / Day	Days of Autonomy	Discharge Limit	Battery Ah Capcity	Batteries in Parallel
51.76	1	0.85	55	1.107
DC System Voltage / Battery Voltage = Batteries in Series * Batteries in Parallel = Total Batteries				
DC System Voltage	DC Battery Voltage	Batteries in Series	Batteries in Parallel	Total Batteries
12	12	1	1	1

TABLE III: PV array sizing calculations for the SPVR system. The results indicate that approximately 8-9, 100 W panels are needed to power the SPVR system assuming that each of these panels.

Array Sizing Worksheet				
(Avg Ah/day) / (Battery Efficiency) / (Peak Sun hrs/day) = Avg peak Amps/Day				
Ave Ah/Day	Battery Efficiency	Peak Sun hrs/ Day	Avg Pk Amps/Day	
51.76	0.99	1.1	47.53	
(Avg. Peak Amps) / (Peak Amps/Module) = Modules in Parallel				
Avg. Peak Amps / Day	Peak Amps/module	Modules in Parallel		
47.53	5.75	8.27		
DC System Voltage / Nominal Module Voltage = Modules in Series * Modules in Parallel = Total Modules				
DC System Voltage	Nominal Module Voltage	Modules in Series	Modules in Parallel	Total Modules
12	12	1	1	1

TABLE IV: Charge controller sizing worksheet calculations for the SPVR system. The results indicate that the controller must have a max DC amperage rating of at least 3.33 A. The charge controller used could handle up to 20 A.

Controller Sizing Worksheet			
*Module Isc * Module in Parrallel * 1.25 = Array Isc*			
Module Isc	Modules in Parallel	1.25	Array Isc
5.75	1	1.25	7.1875
DC Total Watts / DC Syst Voltage = Max DC Load Amps			
DC Total Watts	DC System Voltage	Max DC Load Amps	
40	12	3.333333333	

TABLE V: PV module to charge controller wire sizing worksheet which is based on NEC and AWG wiring standards. The results indicate that the optimal wire sizing for wires connecting the PV module to the charge controller would be 18 AWG assuming a component distance of less than 5 feet based on the AWG reference: https://bit.ly/2SDGHz7

PV Module to Charge Controller Wire Sizing Worksheet (Required Safety Factor, Industry-Based)				
*(Short Circuit Current) * (# Modules in Parallel) = Total Amps * 1.25 * 1.25 = NEC Required Amps*				
Module Isc	Modules in Parallel	Total Amps	1.25 * 1.25 (Safety)	NEC Required Amps
5.75	1	5.75	1.5625	8.98
NEC REQUIREMENTS - PART A				
NEC Wire Size (Table)	Amperage * Ambient Temp. Correction Factor		Ampacity Calculated	Temperature
18 AWG	6	1.08	6.48	60*C
NEC REQUIREMENTS - PART B				
System Voltage (V)	Total Amps (NEC)	One Way Distance	Voltage Drop (%)	Optimal Wire Size
12	8.98	LESS THAN 5FT	3.00	18AWG

TABLE VI: Fuse sizing calculations for the SPVR unit. The results show that there must be a minimum array to controller fuse rating of 8.98 Amps assuming a 5.75 Amp module short circuit current. The fuse selected for this application was oversized to be 20 Amps. In addition, the controller to battery/load was sized at 20 Amps. The charge controller already has a built-in load protection fuse that address this requirement.

Fuse Worksheet (Optional Safety Factor, Industry-Based)				
*ARRAY TO CONTROLLER: (Current Per Module) * (Modules in Parallel) = Total Amps * 1.25 = Industry Fuse Rating*				
Current Per Module (Isc)	Modules in Parallel	Total Amps	1.25 * 1.25 (Safety)	NEC Required Amps
5.75	1	5.75	1.5625	8.98
*CONTROLLER TO BATTERY/LOAD: Charge Ctrl. Amp. Rating * Opt. Safety Factor = Positive Fuse Rating*				
Charge Ctrl. Amp. Rating	Optional Safety Factor	Optional Safety Factor	Positive Fuse Rating	
20.00	1	1.00	20.00	

Appendix C: MATLAB Calculations for PV System Components & Theoretical Power Calculations

```
% Capstone Group: Ross Sison, Ryan Schofield, Justin Ringle, Daren Fernandez
% MATLAB Code Author: Ross Sison
% Phase 2 Capstone Project: Refined System Calculations
% Calculations Include: PV System Power, Cooler Performance,
% Load Power Consumption, and Temperature-Related Calculations
% Created: February 2, 2020
% Updated: May 22, 2020

% Author's Note: The formula's and values placed in this MATLAB
% code represent the final result of our calculations.  Data
% inputted for the variables section were based on the results of
% experiments, average values, and nominal system ratings. These
% calculations provide estimates for the power, voltage, current
% and TEC thermal behavior for the PV System. The calculations
% and the associated assumptions will need to be refined in future
% developments that stem from this project.
```

Variables

```
% For the Calculation of Solar Energy Output
% Total Solar Panel Area (square meters)
A = 0.7363980;
% Solar Panel Energy Conversion Efficiency (%)
r = 0.21;
% Annual Average Solar Raditation (kW/m^2)
H = 200;
% Performance Ratio (0.5-0.9, default at 0.75)
PR = 0.75;
% Inverter losses (4-10%)
Invl = 1-0.04;
% Temperature losses (5-20%)
Templ = 1-0.05;
% DC Cable Losses (1-3%)
DCcl = 1-0.01;
% Shading Losses (0-80%)
Shdl = 1-0.10;
% Weak Solar Radiation Losses
WkSlrl = 1-0.07;
% Maintenance Losses (i.e. Dust, Debris, etc...) (0-2%)
Ml = 1-0.02;
% Optimal Solar Irradiance (W/m^2)
OSI = 1000;

% For the Calculation of Power Capabilities of Main Components
% PV Open Circuit Voltage (V)
V_oc = 21.6;
% PV Optimum Voltage (V)
V_op = 17.9;
% Nominal Voltage (V)
V_nom = 12;
% PV Optimum Current (A)
I_op = 5.29;
```

```
% PV Short Circuit Current (A)
I_sc = 6.24;
% PV Charge Controller Rated Current Limit (A)
I_ccl = 20;
% Battery Peak DC Power Output (W)
P_max = 60;
% Battery Output DC Current (Ah)
I_out = 43;
% Battery Nominal DC Voltage (V)
V_nom = 12;
% Fridge Power Consumption (W)
P_fridge = 57.6;

% For Calculations Pertaining to Power Dissipation
% Resistance of Copper Wire in Ohms (approximate for 100m)
% Assuming a resistivity of copper at 1.72e-8 at 20 deg. C
% Assuming the width of the wire is 2.5e-6 sq. meters
% Length of wire is in meters
Rs_copper = 1.72e-8;
Wd_copper = 2.5e-6;
L_wire = 20;
I_wire = I_out;

% For Calculations Pertaining to Thermal Performance
% of the Igloo Thermoelectric Cooler (28-Quart)
% --- Performance Specification Inputs ---
% Hot Side or Outer Heat Sink Temperature (in K)
Th = 295;
% Cold Side Temperature (in K)
Tc = 259;
% Maximum Temperature Difference Betw. Cold & Hot Sides (K)
dTmax = 69.65;
% Maximum Current Draw from Cooler (A)
```

```
Imax = 3.33;
% Maximum Voltage Draw from Cooler (A)
Vmax = 4.78;
% --- Operating Condition Inputs ---
% Operating Voltage (V)
Vop = 12;
% Operating Current (A)
Iop = 4.8;
% Operating Current - Maximum (A)
Imop = 6;
% Operating Hot Side (K)
Toph = 323;
% Operating Cold Side (K)
Topc = 259;
% Ambient Temperature (K)
Ta = 293;
% Given Operating Difference in Temperature (K)
dT = abs(Toph-Topc);
% Average Estimated Cooler Thickness (cm)
CT = 2.621;
% --- N and G Value Inputs ---
% N-value (Number of Pair of Thermoelectric Current) - Assumption
N = 100000;
% G-value (Area/Length of Thermoelectric Current, cm) - Assumption
G = 0.072;

% For Calculations on Temperature and Load Power Consumption
% For reference, the vaccine storage temperature range is
% 2-8 degrees Celsius or 35.6-46.4 degrees Fahrenheit
% for most vaccines.  The desired avg. is 5 deg. Celsius.
% From the Load II test done on 2/6/2020, the cooler
% was able to reduce the temperature within the acceptable
% range of about 8 to 4.7 degrees Celsius without thermal mass.
% This range is used as the basis for extracting the raw data for the
```

```
% cycle-on time calculations. The cycle-off time was based on
% the amount of time for the interior of the cooler to raise
% from approx. 2 to 8 degrees Celsius.

% Duration (h) for interior temp. to reach Vaccine Max Temp.
% This is the cycle-off time
t_off = 11;
% Duration (h) for interior temp. to reach Vaccine Min Temp.
% This is the cycle-on time
t_on = 10.25;
% Load Voltage Requirement (V)
V_load = 12;
% Current Draw of Load (A)
I_load = 4.8;

% For Calculations Pertaining to Battery Performance
% Battery Capacity - Nominal (Ah)
BCN = 75;
% Battery Voltage - Nominal (V)
BVN = 12;
% Weight of Battery (kg)
BW = 16.3293;
% Depth of Discharge Limit (out of 1)
DOD = 0.8;
% Rated Capacity Error (out of 1)
RCE = 0.5;
% Maximum Battery Current (Discharge) - Assume 1HR Full Operation, A
I_maxbatt = 75;
```

Main PV System Calculations

```
% Estimated Solar Energy Output
E_out = A * r * H * PR;
fprintf('Estimated Solar Energy Output: %f kWh \n', E_out)

% Estimated Solar Energy Output with Losses Considered
E_outli = A * r * H * PR * Invl * Templ * DCcl * Shdl * WkSlrl * Ml;
fprintf('Estimated Solar Energy Output with Losses Considered: %f kWh \n', E_out

% PV Panel Maximum Power Output
P_max = V_oc * I_sc;
fprintf('Maximum PV Module Power Output: %f W \n', P_max)

% PV Panel Optimal Power Output
P_op = V_op * I_op;
fprintf('Maximum PV Optimal Power Output: %f W \n', P_op)

% PV Panel Nominal Power Output
P_nom = I_op * V_nom;
fprintf('Maximum PV Nominal Power Output: %f W \n', P_nom)

% Charge Controller Nominal Power Ouptut
P_cc = V_nom * I_ccl;
fprintf('Charge Controller Nominal Power Ouptut: %f W \n', P_cc)

% Resistivity of Wire
R_wire = ((Rs_copper*100)/Wd_copper);
fprintf('Copper Wire Resistivity: %f Ohms \n', R_wire)

% Power Dissipated Through Wire
Pwire_dissipated = I_op * (R_wire)^2;
fprintf('Power Dissipated Through Wire: %f W \n', Pwire_dissipated)
```

```
% Power Dissipated Through Fridge
fprintf('Power Dissipated Through Fridge: %f W \n', P_fridge)

% Nominal Maximum Operating Current Through Fridge
Ifridge = P_fridge/V_nom;
fprintf('Nominal Maximum Operating Current Through Fridge: %f A \n', Ifridge)

% Charge Controller Switch Current (CC-Load -> CC-Battery & Load) (A)
% Assumed to be equal to nominal operating current of fridge
I_sw = Ifridge;
fprintf('Charge Controller Switch Current (from CC->Load to CC->Battery & Load): %f A \n', I_sw)

% Charge Controller Switch Current (CC-Load -> CC-Battery & Load) (A)
% Assumed to be equal to nominal operating current of fridge
I_battmaxsi = I_op - I_sw;
fprintf('Current to Battery at Maximum Solar Irradiance: %f A \n', I_battmaxsi)

% Solar Irradiance Resulting in Switch (CC-Load -> CC-Battery & Load) (A)
SI_sw = OSI*(I_sw/I_op);
fprintf('Solar Irradiance Resulting in Switch (from CC->Load to CC->Battery & Load): %f W/m^2 \n \n', SI_sw)
```

```
Estimated Solar Energy Output: 23.196537 kWh
Estimated Solar Energy Output with Losses Considered: 17.179271 kWh
Maximum PV Module Power Output: 134.784000 W
Maximum PV Optimal Power Output: 94.691000 W
Maximum PV Nominal Power Output: 63.480000 W
Charge Controller Maximum Power Ouptut: 240.000000 W
Copper Wire Resistivity: 0.688000 Ohms
Power Dissipated Through Wire: 2.503990 W
Power Dissipated Through Fridge: 57.600000 W
Nominal Maximum Operating Current Through Fridge: 4.800000 A
Charge Controller Switch Current (from CC->Load to CC->Battery & Load): 4.800000 A
Current to Battery at Maximum Solar Irradiance: 0.490000 A
Solar Irradiance Resulting in Switch (from CC->Load to CC->Battery & Load): 907.372401 W/m^2
```

Igloo Thermoelectric Cooler Thermal Performance

```
% Z Value (Figure of Merit, s^2/(rho*k)*(K^-1))
Z = (2*dTmax)/(Th-dTmax);
fprintf('Z Value, Figure of Merit: %f s^2/(rho*k)*(K^-1) \n', Z)

% Sm Value (Device Seebeck Voltage, V/K)
Sm = Vmax/Th;
fprintf('Sm Value, Device Seebeck Voltage: %f V/K \n', Sm)
```

```
% Km Value (Device Thermal Conductance, W/K)
Km = ((Th-dTmax)*Vmax*Imax)/(2*Th*dTmax);
fprintf('Km Value, Device Thermal Conductance: %f W/K \n', Km)

% Rm Value (Device Electrical Resistance, Ohms)
Rm = ((Th-dTmax)*Vmax)/(Th*Imax);
fprintf('Rm Value, Device Electrical Resistance: %f Ohms \n', Rm)

% Qc Value (Heat Absorbed on Cold Surface, W)
Qc = (Sm*Tc*Iop)-(0.5*((Iop)^2)*Rm)-(Km*dT);
fprintf('Qc Value, Heat Absorbed on Cold Surface: %f W \n', Qc)

% Qp Value (Power Input of TEC, W)
Qp = Iop*Vop;
fprintf('Qp Value, Power input of TEC: %f W \n', Qp)

% Vmax Value at Maximum External-Internal Temperature Difference
Vcmax = (Sm*dT)+(Imop*Rm);
fprintf('Vmax at Maximum External-Internal Temperature Difference: %f V \n', Vcm

% COP Value (Coefficient of Performance)
COP = Qc/Qp;
fprintf('Coefficient of Performance (COP): %f \n', COP)

% R_heat sink Value (Thermal Resistance, K/W)
R_heatsink = (Th-Ta)/(Qc+Qp);
fprintf('Thermal Resistance of Heat Sink: %f K/W \n', R_heatsink)

% rho(p) Value (Rm = 2pN/G) (Cooler Matl. Resistivity, Ohm-cm)
p = (Rm*G)/(2*N);
fprintf('Rho(p) Value, Cooler Material Resistivity: %f Ohm-cm \n', p)

% s Value (Sm = 2sN) (Cooler Matl. Seebeck Coefficient, V/K)
s = Sm/(2*N);
fprintf('s Value, Cooler Material Seebeck Coefficient: %f V/K \n', s)
```

```
% k Value (Km = 2NkG) (Cooler Matl. Thermal Conductivity, W/cm-K)
k = Km/(2*N*G);
fprintf('k Value, Cooler Material Thermal Conductivity: %f W/cm-K \n', k)

% r Value (Cooler Matl. Thermal Resistivity, cm^2*K/W)
rcalc = CT*(1/k);
fprintf('r Value, Cooler Material Thermal Resistivity: %f cm^2*K/W \n', rcalc)

% Heat Flux (W/m^2)
HF = k*(Ta)*(1/CT)*(100/1)^2;
fprintf('Heat Flux: %f W/m^2 \n \n', HF)
```

```
Z Value, Figure of Merit: 0.618150 s^2/(rho*k)*(K^-1)
Sm Value, Device Seebeck Voltage: 0.016203 V/K
Km Value, Device Thermal Conductance: 0.087288 W/K
Rm Value, Device Electrical Resistance: 1.096527 Ohms
Qc Value, Heat Absorbed on Cold Surface: 1.925609 W
Qp Value, Power input of TEC: 57.600000 W
Vmax at Maximum External-Internal Temperature Difference: 7.616177 V
Coefficient of Performance (COP): 0.033431
Thermal Resistance of Heat Sink: 0.033599 K/W
Rho(p) Value, Cooler Material Resistivity: 0.000000 Ohm-cm
s Value, Cooler Material Seebeck Coefficient: 0.000000 V/K
k Value, Cooler Material Thermal Conductivity: 0.000006 W/cm-K
r Value, Cooler Material Thermal Resistivity: 432387.323364 cm^2*K/W
Heat Flux: 6.776332 W/m^2
```

Temperature and Expected Load Power Consumption

```
% Number of Cycle On + Cycle Off Times in 24 Hours
Ncoft = (24)/(t_off+t_on);
fprintf('Number of Cycle ON & Cycle OFF Times in 24 Hours: %f Times \n', Ncoft)

% Duration of One Cycle-On and Cycle-Off Period (h)
Tcofp = (t_off+t_on);
fprintf('Duration of One Cycle-ON and Cycle-OFF Period: %f h \n', Tcofp)

% Total Cycle On Time per Day (h)
t_CON = (t_on/Tcofp)*24;
fprintf('Total Cycle ON Time per Day: %f h \n', t_CON)

% Total Cycle Off Time per Day (h)
t_COFF = (t_off/Tcofp)*24;
fprintf('Total Cycle OFF Time per Day: %f h \n', t_COFF)

% Average Current Capacity Requirement of Load per Day
I_lavgd = (I_load*t_CON);
fprintf('Average Current Capacity Requirement of Load per Day: %f Ah \n', I_lavgd)

% Average Power Capacity Requirements of Load per Day
P_lavgh = I_lavgd*V_nom;
fprintf('Average Power Capacity Requirements of Load per Day: %f W \n', P_lavgh)

% Average Power Capacity Requirements of Load per Hour
P_lavgd = P_lavgh/24;
fprintf('Average Power Capacity Requirements of Load Per Hour: %f Wh \n \n', P_lavgd)
```

```
Number of Cycle ON & Cycle OFF Times in 24 Hours: 1.129412 Times
Duration of One Cycle-ON and Cycle-OFF Period: 21.250000 h
Total Cycle ON Time per Day: 11.576471 h
Total Cycle OFF Time per Day: 12.423529 h
Average Current Capacity Requirement of Load per Day: 55.567059 Ah
Average Power Capacity Requirements of Load per Day: 666.804706 W
Average Power Capacity Requirements of Load Per Hour: 27.783529 Wh
```

Battery Performance Calculations

```
% Battery Capacity (Ah)
fprintf('Nominal Battery Capacity: %f Ah \n', I_lavgd)

% Battery Capacity (Wh)
BC = I_lavgd*BVN;
fprintf('Nominal Battery Capacity: %f Wh \n', BC)

% Specific Power (Wh/kg)
BSP = BC/BW;
fprintf('Specific Power: %f Wh/kg \n', BSP)
```

```
Nominal Battery Capacity: 55.567059 Ah
Nominal Battery Capacity: 666.804706 Wh
Specific Power: 40.834862 Wh/kg
```

Reference Links

```
% --- Power Related Equations ---
% https://photovoltaic-software.com/principle-ressources/how-calculate-solar-energy-power-pv-systems
% https://www.electronics-tutorials.ws/resistor/resistivity.html
% http://www.indiaenergyportal.org/subthemes.php?text=solar

% --- Cooling Related Equations ---
% https://www.electronics-cooling.com/2008/08/a-simple-method-to-estimate-the-physical-characteristics-of-a-thermoelectric-cooler-from-vendor-datasheets/
% https://www.sciencedirect.com/topics/chemistry/seebeck-coefficient
% https://insulation.org/io/articles/k-value-u-value-r-value-c-value/
% https://betterhomesbc.ca/products/what-is-r-or-rsi-value/

% --- Temperature, Load Performance ---
% https://www.cdc.gov/vaccines/pubs/pinkbook/downloads/vac-storage.pdf

% --- Battery Related Equations ---
% https://www.powerstream.com/battery-capacity-calculations.htm
% https://power-calculation.com/battery-storage-calculator.php
```

Appendix D: Draft Fusion 360 System Modeling

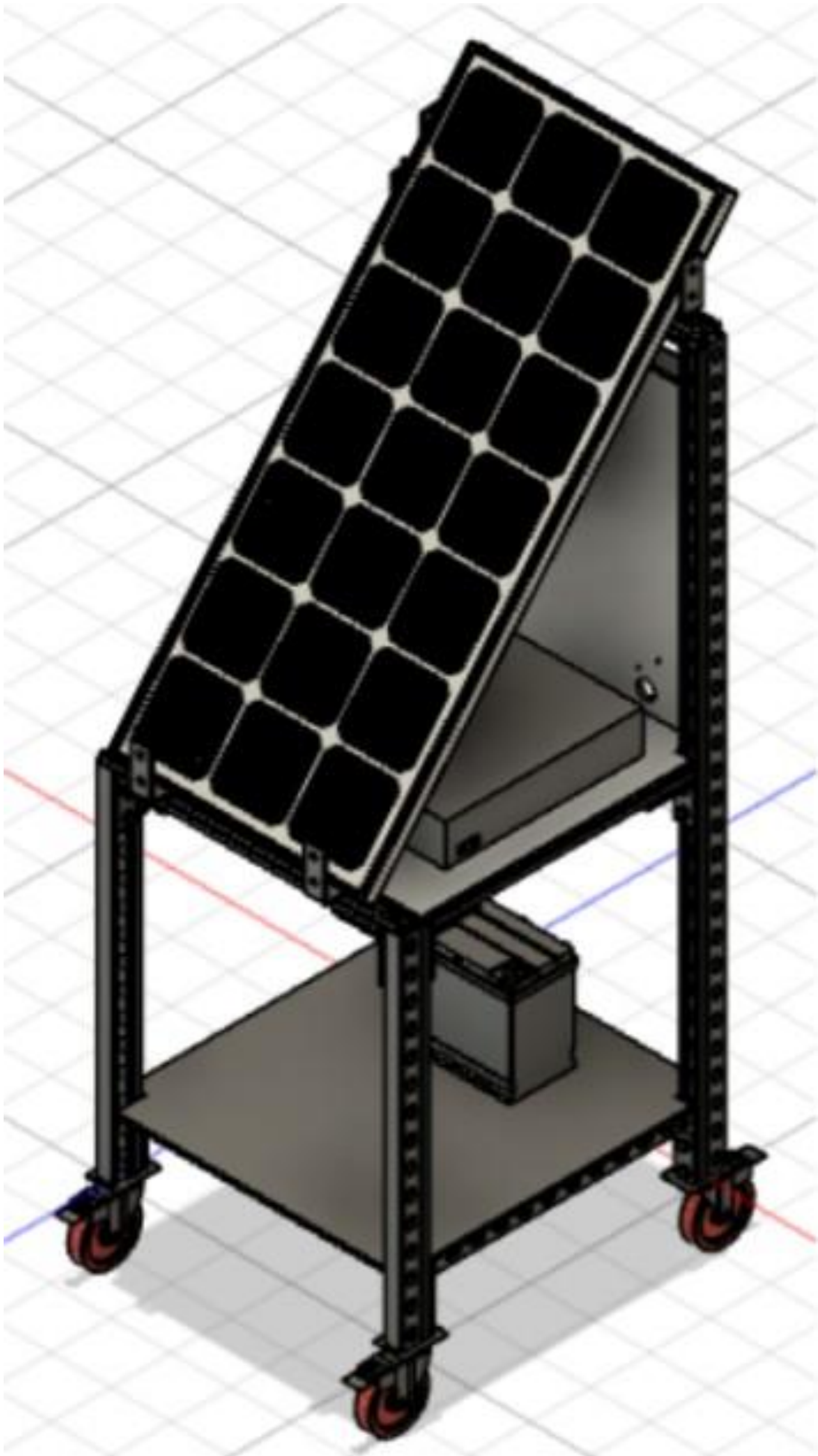

Fig. 6: 3D model of angled frontal view of the PV system trainer that holds the SPVR DC Solar Array Simulator Power Supply, SLA Battery, DC Thermostat Controller, ALLPOWERS Charge Controller, Fusebox, and Load connection ports.

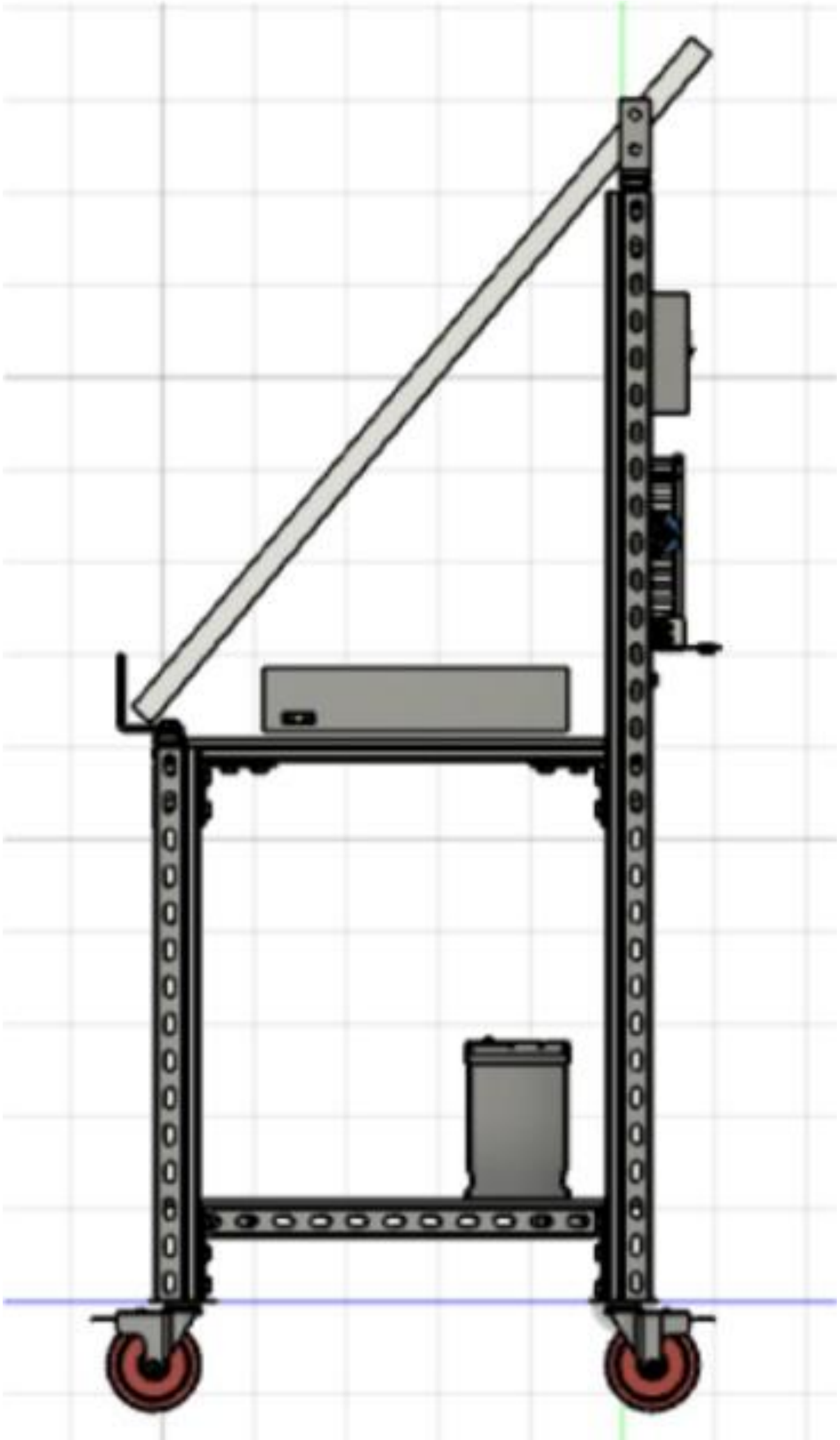

Fig. 7: 3D model of left side view of the PV system trainer for the SPVR unit.

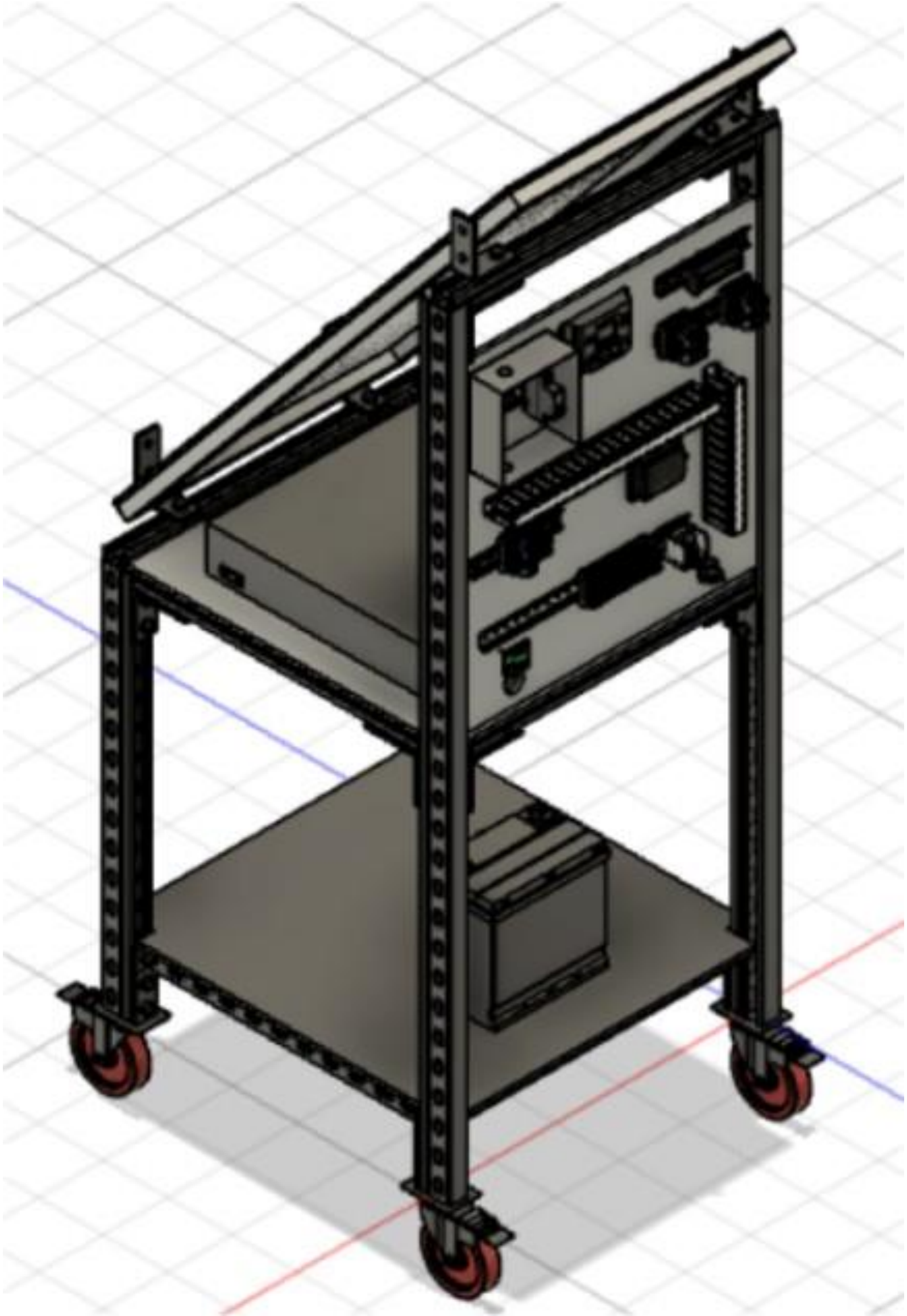

Fig. 8: 3D model showing angled, upper view of PV system trainer for the SPVR unit.

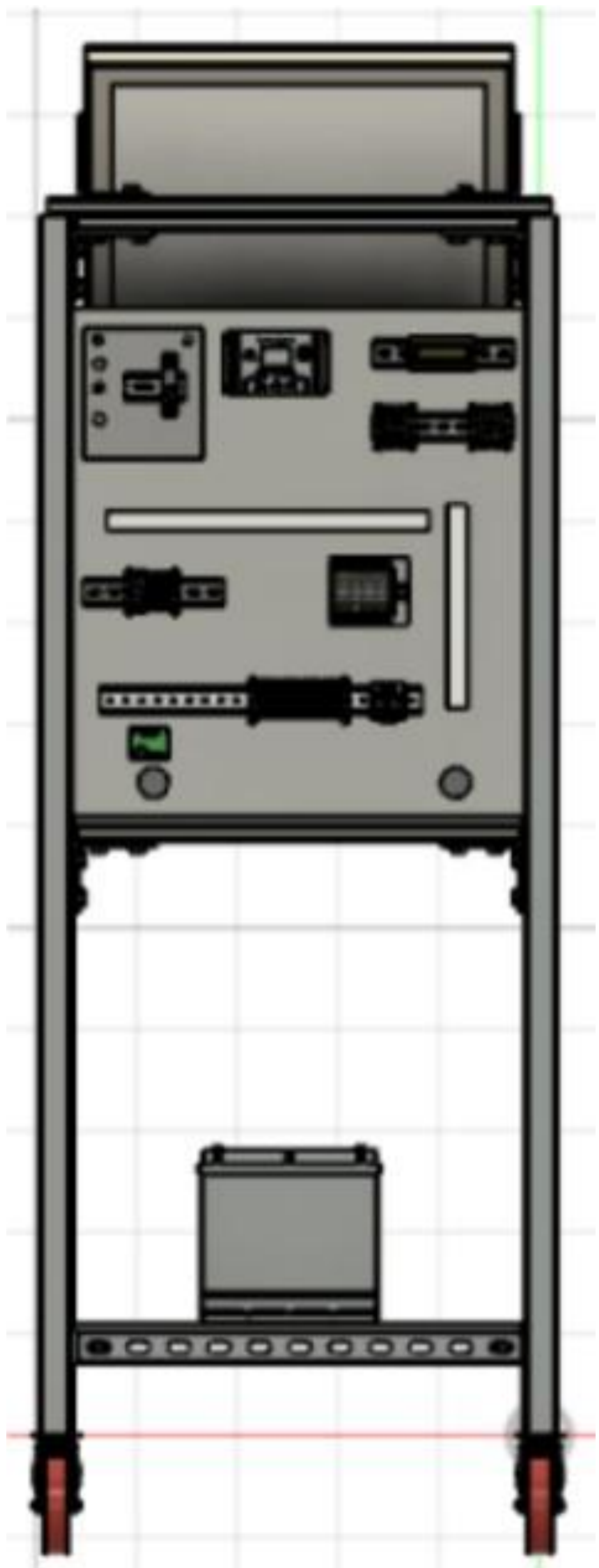

Fig. 9: 3D model showing rear PV system trainer for the SPVR unit. The back panel contains fuses, charge controller, DIN rails, load connection ports.

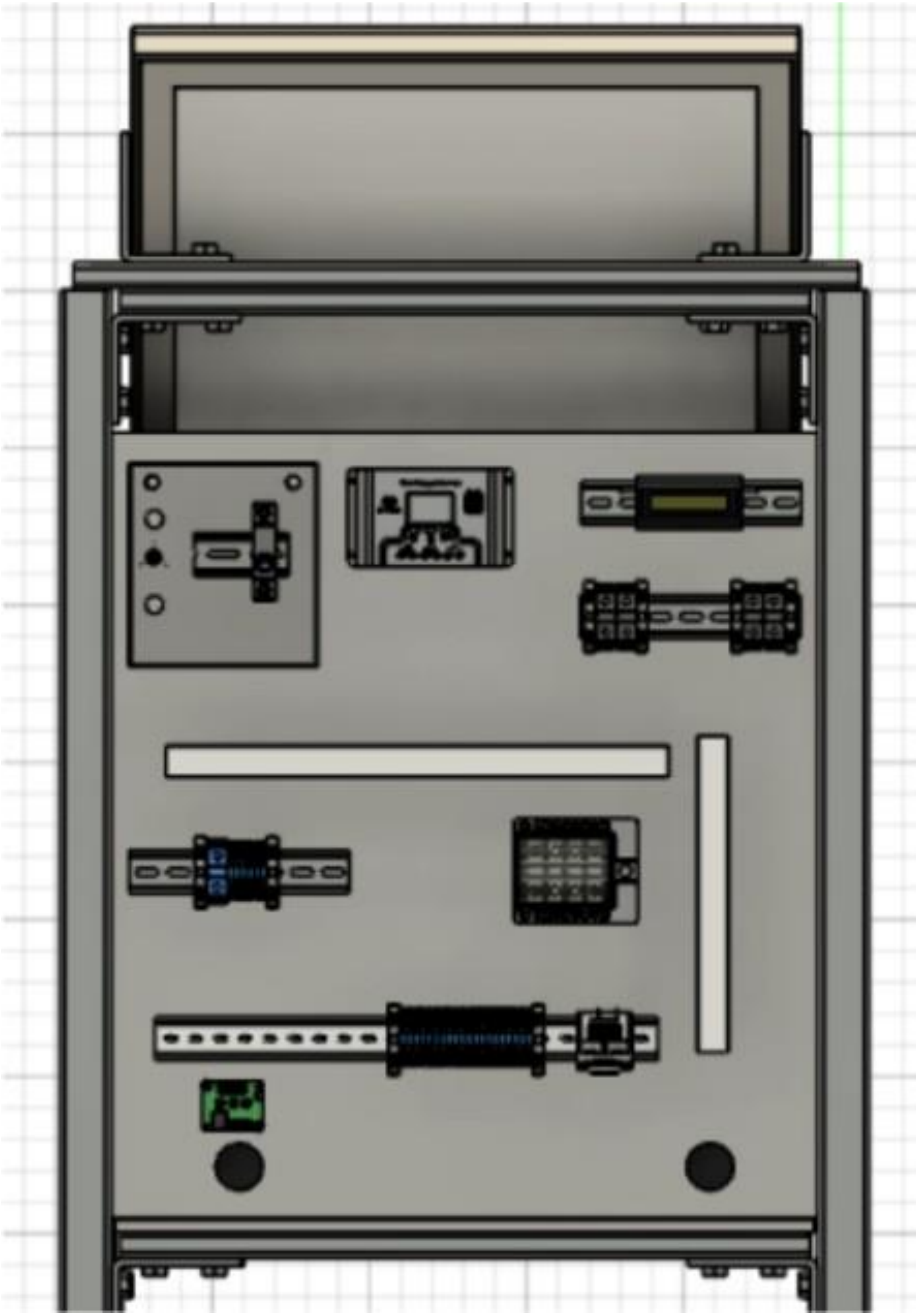

Fig. 10: Close-up of the back panel of PV system trainer for the SPVR unit.

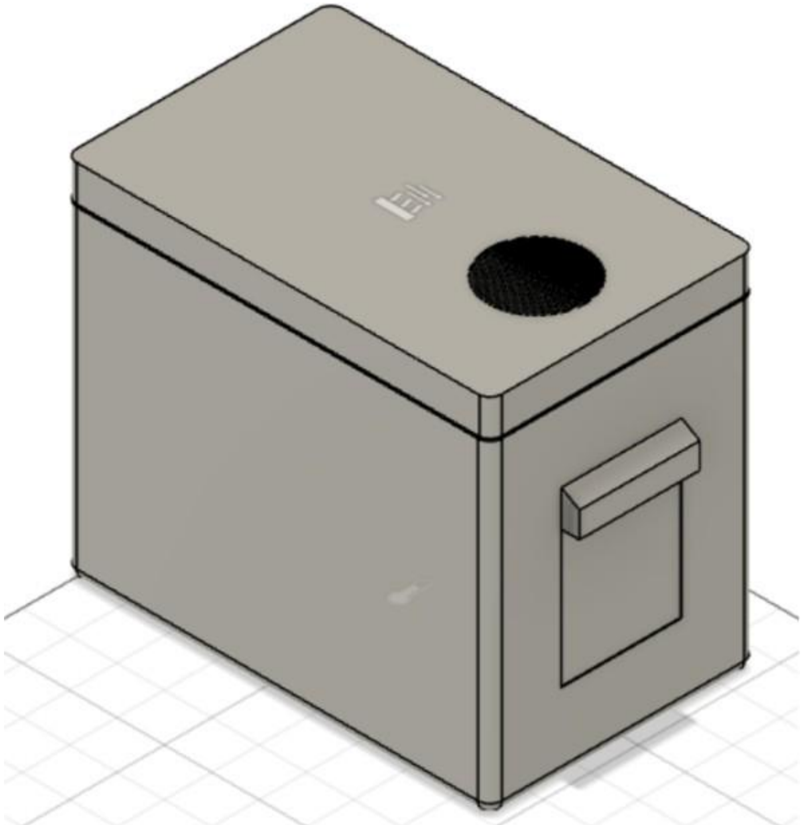

Fig. 11: 3D model of Igloo Thermoelectric Cooler Unit from a front-edge angled view. The surface area of this unit is approx. 0.786 m^2.

Fig. 12: 3D model of Igloo Thermoelectric Cooler from a top-down, side-edge angled view.

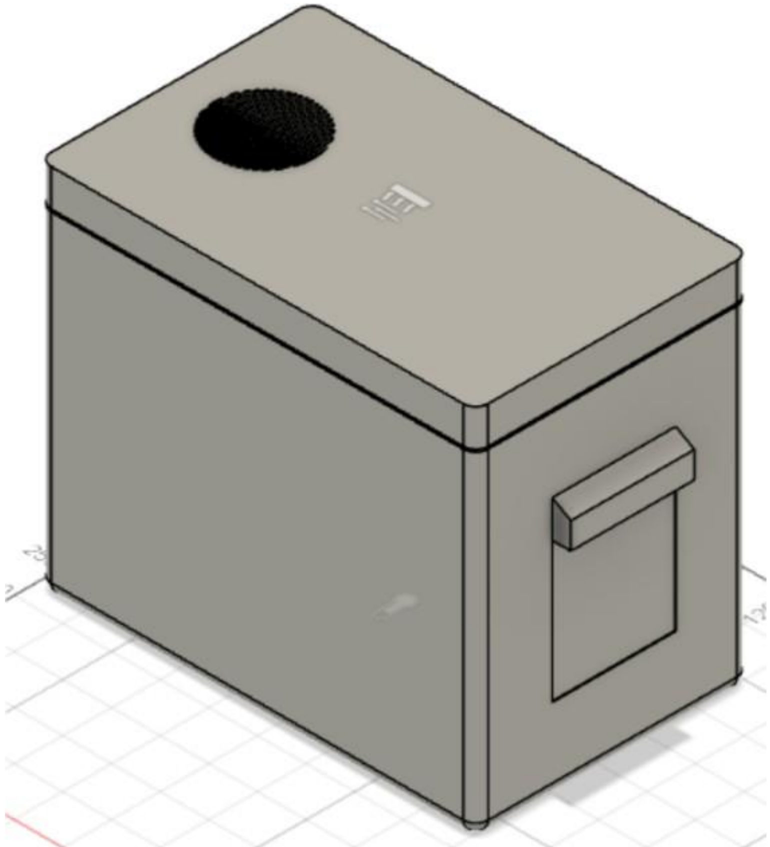

Fig. 13: 3D model of Igloo Thermoelectric Cooler from a back edge angled view.

Appendix E: SPVR System Physical Wiring Diagram

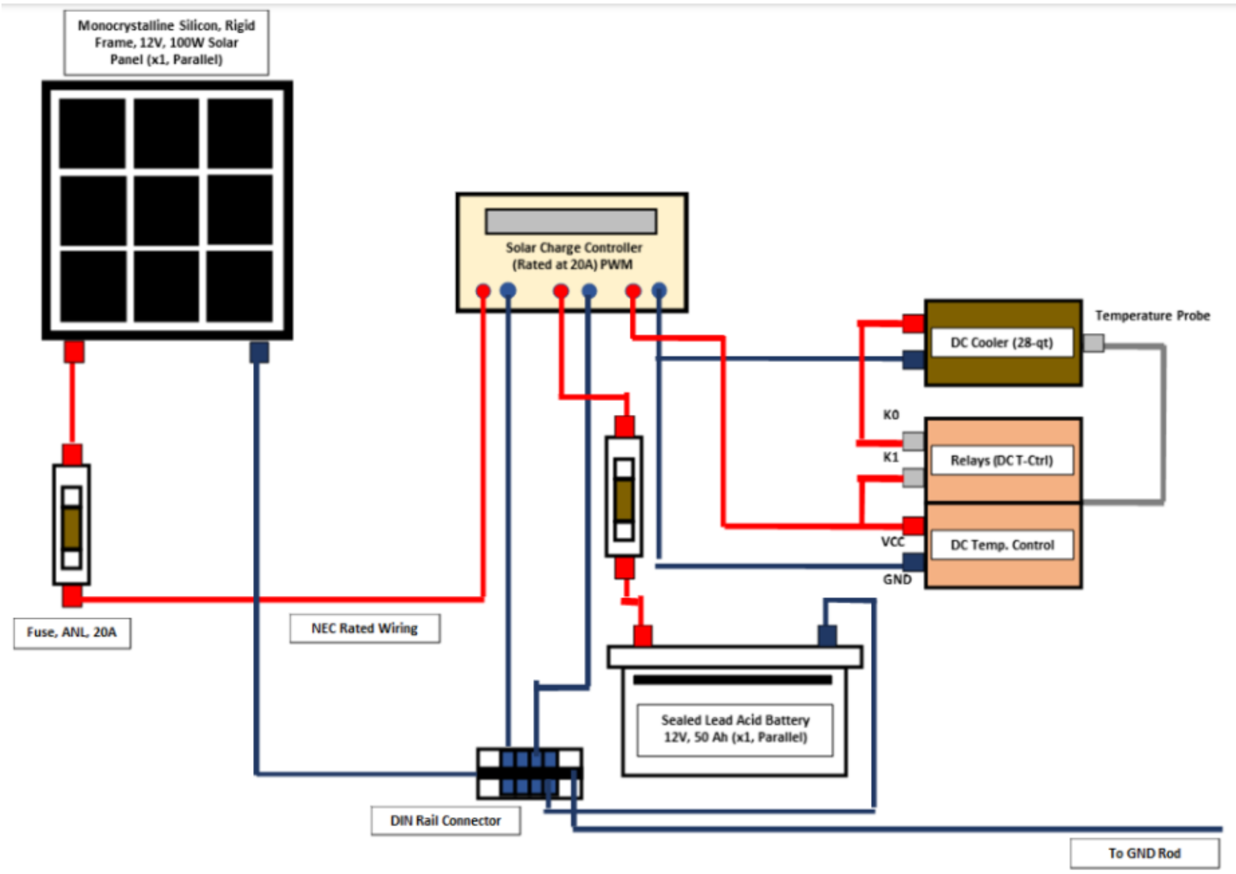

Fig. 14: Physical wiring connection schematic for the SPVR unit. Please note that the Oregon Tech power lab's microgrid building ground connection was used in place of a grounding rod.

Appendix F: Tiered BOMs Tables for the RBC Proposal

BOM Tables are listed in order of decreasing project cost. Please note that the materials listed in Tier 4 have been basis for the ideal design and feasibility analysis.

TABLE VII: Tier 4 RBC proposal bill of materials (i.e., used when the team was applying for Oregon Tech-based funding for this project) which includes the ideal system components for a robust solar-powered vaccine refrigeration unit.

SOLAR-POWERED VACCINE FRIDGE SYSTEM BILL OF MATERIALS AND SERVICES SUMMARY (TIER 4 - IDEAL FUNDING CASE)								
PV SYSTEM COMPONENTS	MODEL	SIZE	COST	WEIGHT (LBS)	QUANTITY	LIFESPAN	TOTAL WEIGHT (LBS)	TOTAL COST
PV Array & Charge Controller (100W)	Renogy	19.9 x 27.2 x 2.8 in	$ 237.99	26.6	1	25 years	26.6	$ 237.99
Batteries	Rockpals	8.9 x 3.9 x 6.3 in	$ 193.99	5.5	1	25 years	5.5	$ 193.99
Wires (Red & Black)	Gear IT	14 AWG, 100 feet	$ 39.99	4.01	1	20 years	4.01	$ 39.99
Wire-to-Fuse Hub Connector (14AWG Fem.)	AIRIC	7.5 x 4.7 x 0.4 in	$ 8.99	0.2	1	20 years	0.2	$ 8.99
FUSE COMPONENTS								
Solar Array-Controller Fuse (9A)	MidNite	1 x 3 x 4 in	$ 24.95	0.2	1	20 years	0.2	$ 24.95
Controller-Battery/Load Fuse Hub (10)	KKMoon Fusebox	7.6 x 6.1 x 2.1 in	$ 10.90	0.31	1	20 years	0.31	$ 10.90
Controller-Battery/Load Fuses (20A)	Renogy	4.8 x 0.8 x 0.8 in	$ 12.60	0.07	1	20 years	0.07	$ 12.60
DIN Rail Connectors (Common Neg.)	Dinkle DK4N	5.2 x 3 x 3 in	$ 13.99	0.1	1	20 years	0.1	$ 13.99
SYSTEM ACCESSORIES								
Accessory / Component Backpack	AmazonBasics Backpack	18 x 8 x 37 in	$ 57.48	4.27	1	50 years	4.27	$ 57.48
Solar Array / Rod Bag	Stansport	50 x 30 in	$ 49.99	1.375	1	50 years	1.375	$ 49.99
Mounting Materials	Renogy Mounts	28 x 1.5 x 2.5 in	$ 49.99	1.4	1	50 years	1.4	$ 49.99
USB Y-Splitter (for Battery)	Andul	9.3 x 5.4 x 0.7 in	$ 8.99	0.2625	1	20 years	0.2625	$ 8.99
Multi Cell Phone Charge Splitter USB Cable	IVVO	8.3 x 4.6 x 0.4 in	$ 10.99	0.13	2	20 years	0.26	$ 21.98
Surge Protector (1785 Joules, 7 Outlets)	Dewenwils	14.5 x 6.2 x 2.2 in	$ 18.99	1	1	20 years	1	$ 18.99
Grounding Rod (4 ft.)	PVGR4	48 x 1 x 4 in	$ 20.95	1.35	1	40 years	1.35	$ 20.95
Wire Multi-Tool (Cut, Crimp, Strip)	Southwire	3.6 x 9.9 x 0.8 in	$ 23.00	0.375	1	40 years	0.375	$ 23.00
Type G Plug Adapter to Type A (US) (x3)	Ceptics	1 x 1 x 1 in	$ 9.99	0.3	1	25 years	0.3	$ 9.99
Extension Cords (1ft) for Batt. Outlets (x3)	FIRMERST	7.9 X 3.9 X 0.8 in	$ 10.99	0.8375	1	20 years	0.8375	$ 10.99
Extension Cords (10ft) for Batt. Outlets (x2)	FIRMERST	12.2 x 3.9 x 1.2 in	$ 16.99	2.15	1	20 years	2.15	$ 16.99
Travel Power Adapter (International)	SublimeWare	5.5 x 3.9 x 3.9 in	$ 19.99	0.4	2	20 years	0.8	$ 39.98
INCLUDED AC LOADS								
Portable Fridge w/ Batt. & Inverter (48W)	Acopower X40A	25.1 x 15 x 18.7 in	$ 539.00	28	1	20 years	28	$ 539.00
INCLUDED DC LOADS								
Cell Phone (SIM not included)	Huawei Honor 8X	6.9 x 3.5 x 2.2 in	$ 215.00	0.39	1	10 years	0.39	$ 215.00
REQUIRED TEST EQUIPMENT								
Wireless Temp. and Humidity Sensor	SensorPush	1.6 x 1.6 x 0.7 in	$ 49.99	0.09	4	10 years	0.36	$ 199.96
Adjustable Timed Plug	Vogelumax	2.9 x 2.4 x 4.3 in	$ 11.99	0.35	2	10 years	0.7	$ 23.98
High Voltage/Amperage Clamp Multimeter	Etekcity	8.2 x 3 x 1.2 in	$ 29.99	0.85	1	10 years	0.85	$ 29.99
Digital Weighing Scale	Smart Weigh	8 x 8 x 1.8 in	$ 33.99	3.9	1	10 years	3.9	$ 33.99
Safety Carrying Harness (x2)	Shoulder Dolly	28 x 9 x 30 in	$ 36.60	3.53	1	5 years	3.53	$ 36.60
REQUIRED SERVICES / SOFTWARE								
Transportation	-	-	-	-	-	-	-	$ 580.00
Product Delivery / Shipping	-	-	-	-	-	-	-	$ 50.00
Food	-	-	-	-	-	-	-	$ 50.00
Storage	-	-	-	-	-	-	-	$ -
Equipment Rental	-	-	-	-	-	-	-	$ -
Software (i.e. Fusion 360, LTSpice, MATLAB)	-	-	-	-	-	-	-	$ -
TOTAL WEIGHT (LBS)							89.1	
TOTAL COST (USD)								$ 2,631.24

TABLE VIII: Tier 3 RBC proposal bill of materials which includes the next best system components for a robust solar-powered vaccine refrigeration unit.

SOLAR-POWERED VACCINE FRIDGE SYSTEM BILL OF MATERIALS AND SERVICES SUMMARY (TIER 3 - PARTIAL FUNDING CASE)								
PV SYSTEM COMPONENTS	MODEL	SIZE	COST	WEIGHT (LBS)	QUANTITY	LIFESPAN	TOTAL WEIGHT (LBS)	TOTAL COST
PV Array & Charge Controller (100W)	Renogy	19.9 x 27.2 x 2.8 in	$ 237.99	26.6	1	25 years	26.6	$ 237.99
Batteries	Rockpals	8.9 x 3.9 x 6.3 in	$ 193.99	5.5	1	25 years	5.5	$ 193.99
FUSE COMPONENTS								
Solar Array-Controller Fuse (9A)	MidNite	1 x 3 x 4 in	$ 24.95	0.2	1	20 years	0.2	$ 24.95
Controller-Battery/Load Fuse Hub (10)	KKMoon Fusebox	7.6 x 6.1 x 2.1 in	$ 10.90	0.31	1	20 years	0.31	$ 10.90
Controller-Battery/Load Fuses (20A)	Renogy	4.8 x 0.8 x 0.8 in	$ 12.60	0.07	1	20 years	0.07	$ 12.60
DIN Rail Connectors (Common Neg.)	Dinkle DK4N	5.2 x 3 x 3 in	$ 13.99	0.1	1	20 years	0.1	$ 13.99
SYSTEM ACCESSORIES								
USB Y-Splitter (for Battery)	Andul	9.3 x 5.4 x 0.7 in	$ 8.99	0.2625	1	20 years	0.2625	$ 8.99
Multi Cell Phone Charge Splitter USB Cable	IVVO	8.3 x 4.6 x 0.4 in	$ 10.99	0.13	2	20 years	0.26	$ 21.98
INCLUDED AC LOADS								
Portable Fridge w/ Batt. & Inverter (48W)	AcopowerX40A	25.1 x 15 x 18.7 in	$ 539.00	28	1	20 years	28	$ 539.00
REQUIRED TEST EQUIPMENT								
Wireless Temp. and Humidity Sensor	SensorPush	1.6 x 1.6 x 0.7 in	$ 49.99	0.09	4	10 years	0.36	$ 199.96
Adjustable Timed Plug	Nearpow	2.9 x 2.4 x 4.3 in	$ 13.99	0.35	2	10 years	0.7	$ 27.98
REQUIRED SERVICES / SOFTWARE								
Product Delivery / Shipping	-	-	-	-	-	-	-	$ 50.00
Storage	-	-	-	-	-	-	-	$ -
Equipment Rental	-	-	-	-	-	-	-	$ -
Software (i.e. Fusion 360, LTSpice, MATLAB)	-	-	-	-	-	-	-	$ -
TOTAL WEIGHT (LBS)							62.3625	
TOTAL COST (USD)								$ 1,342.33

TABLE IX: Tier 2 RBC proposal bill of materials.

SOLAR-POWERED VACCINE FRIDGE SYSTEM BILL OF MATERIALS AND SERVICES SUMMARY (TIER 2 - MINIMAL FUNDING CASE)								
PV SYSTEM COMPONENTS	MODEL	SIZE	COST	WEIGHT (LBS)	QUANTITY	LIFESPAN	TOTAL WEIGHT (LBS)	TOTAL COST
PV Array and Charge Controller (100W)	DOKIO	40 x 21 x 0.5 in	$ 144.77	6	1	25 years	6	$ 144.77
Batteries	Rockpals	8.9 x 3.9 x 6.3 in	$ 193.99	5.5	1	25 years	5.5	$ 193.99
FUSE COMPONENTS								
Solar Array-Controller Fuse (9A)	MidNite	1 x 3 x 4 in	$ 24.95	0.2	1	20 years	0.2	$ 24.95
Controller-Battery/Load Fuse Hub (10)	KKMoon Fusebox	7.6 x 6.1 x 2.1 in	$ 10.90	0.31	1	20 years	0.31	$ 10.90
Controller-Battery/Load Fuses (20A)	Renogy	4.8 x 0.8 x 0.8 in	$ 12.60	0.07	1	20 years	0.07	$ 12.60
DIN Rail Connectors (Common Neg.)	Dinkle DK4N	5.2 x 3 x 3 in	$ 13.99	0.1	1	20 years	0.1	$ 13.99
SYSTEM ACCESSORIES								
Multi Cell Phone Charge Splitter USB Cable	IVVO	8.3 x 4.6 x 0.4 in	$ 10.99	0.13	2	20 years	0.26	$ 21.98
INCLUDED AC LOADS								
Portable Fridge w/ Inverter (27W)	Alpicool CX40	23.1 x 14.9 x 15.4 in	$ 279.00	28.7	1	20 years	28.7	$ 279.00
REQUIRED TEST EQUIPMENT								
Wireless Temp. and Humidity Sensor	SensorPush	1.6 x 1.6 x 0.7 in	$ 49.99	0.09	4	10 years	0.36	$ 199.96
Adjustable Timed Plug	Nearpow	2.9 x 2.4 x 4.3 in	$ 13.99	0.35	2	10 years	0.7	$ 27.98
REQUIRED SERVICES								
Product Delivery / Shipping	-	-	-	-	-	-	-	$ 50.00
Storage	-	-	-	-	-	-	-	$ -
Equipment Rental	-	-	-	-	-	-	-	$ -
Software (i.e. Fusion 360, LTSpice, MATLAB)	-	-	-	-	-	-	-	$ -
TOTAL WEIGHT (LBS)							42.2	
TOTAL COST (USD)								$ 980.12

TABLE X: Tier 1 of the RBC proposal bill of materials (no funding option). Please note that ultimately the team was able to contribute a small amount of out-of-pocket expenses; acquire limited funding from Oregon Tech's Student Project Fees (FEGP) fund; and use donated materials from OIT and Richard Ellis which made the build and test phase of this project possible.

SOLAR-POWERED VACCINE FRIDGE SYSTEM BILL OF MATERIALS AND SERVICES SUMMARY (TIER 1 - NO FUNDING CASE)								
RESEARCH & DESIGN PROJECT ONLY								
Software (i.e. Fusion 360, LTSpice, MATLAB)	-	-	-	-	-	-	-	$ -
TOTAL WEIGHT (LBS)								
TOTAL COST (USD)								$ -

TABLE XI: Tier 4 RBC Proposal Bill of Materials list which complied with UL Safety Standards.

SOLAR-POWERED VACCINE FRIDGE SYSTEM UL LISTED DEVICES								
PV SYSTEM COMPONENTS	MODEL	SIZE	COST	WEIGHT (LBS)	QUANTITY	LIFESPAN	TOTAL WEIGHT (LBS)	TOTAL COST
PV Array and Charge Controller (100W)	DOKIO	40 x 21 x 0.5 in	$ 144.77	6	1	25 years	6	$ 144.77
Wires (Red & Black)	Gear IT	14 AWG, 100 feet	$ 39.99	4.01	1	20 years	4.01	$ 39.99
DIN Rail Connectors (Common Neg.)	Dinkle DK4N	5.2 x 3 x 3 in	$ 13.99	0.1	1	20 years	0.1	$ 13.99
Extension Cords (1ft) for Batt. Outlets (x3	FIRMERST	7.9 X 3.9 X 0.8 in	$ 10.99	0.8375	1	20 years	0.8375	$ 10.99
Extension Cords (10ft) for Batt. Outlets (x	FIRMERST	12.2 x 3.9 x 1.2 in	$ 16.99	2.15	1	20 years	2.15	$ 16.99
Adjustable Timed Plug	Vegelumax	2.9 x 2.4 x 4.3 in	$ 11.99	0.35	2	10 years	0.7	$ 23.98

Appendix G: Project Bill of Materials

SPVR Unit Bill of Equipment and Materials Record

Assembly Name :	**Solar-Powered Vaccine Refrigeration Unit**
Revision Date :	11-May-20
Part Count :	78
Total Worth of Assembly :	$8,733.53
Total Team Expenses :	$44.35

Part #	Part Name	Description	Qty	Unit Cost	Team Expenses
RNG-100D-SS	Renogy 100W Monocrystalline Solar Panel	Solar Panel Unit	1	$124.99	OIT Provided
B007ZYH4BH	Igloo Iceless Thermoelectric Cooler	Refrigeration Unit	1	$91.28	Richard Ellis Provided
B00KQX5GSC	ExpertPower 12V 55Ah Lead Acid Battery	Deep Cycle Lead Acid Battery	1	$106.00	OIT FEGP Funded
SLC10004	Duracell 3.8 Amp Battery Charger (6V / 12V)	Charger for Deep Cycle Lead Acid Battery	1	$69.99	OIT Provided
289/FVF	Fluke 289/FVF FlukeView Forms Combo Kit	Master Multimeter for Temperature, Voltage, and Current Measurement	3	$719.99	OIT Provided
B01AEQ9X9I	SensorPush Wireless Thermometer/Hygrometer	Secondary Temperature Measurement Device (with Cloud-Based Data Records)	4	$49.99	OIT Provided
Model: 8512	BK Precision 8512 DC Electronic Load	DC Electronic Load Simulator	1	$2,795.00	OIT Provided
WH1436A	WILLHI 110V Temperature Controller/Digital Thermostat	Temperature Sensor and Thermostat	1	$29.99	Ross Sison Provided
P4400-VP	Kill-A-Watt Power Meter	Measurement of Load Power, Amperage, Frequency, Power Factor, Usage Time	1	$33.61	Ross Sison Provided
B004K8RF10	Indoor Thermometer and Hygrometer	Backup Temperature Sensor	1	$11.52	Ross Sison Provided
B00006B81E	Tripp Lite 1 Outlet Portable Surge Protector	Surge Protection for AC Loads	1	$10.00	Ross Sison Provided
35266212691	12V AC Converter Adapter for Igloo	AC Power Supply Adapter	1	$12.99	Richard Ellis Provided

CS-579B4	Faylapa 12-Way Fuse Block	Fuse Block	1	$17.99	OIT Provided
B076Y5BXD9	LM YN DC 12V Thermostat Controller Module (Amazon)	Temperature Display and Controller Board (Ryan Schofield's Purchase)	1	$10.99	$10.99
B07DFT2WDS	DROK 12V DC Time Delay Relay (Amazon)	Timer for PV Cooler Operation Limiting (Ryan Schofield's Purchase)	1	$13.89	$13.89
227380	AA Batteries, 48 Pack (Costco)	Replacement Batteries for Fluke 289 Digital Multimeters (Ryan Schofield's Purchase)	1	$15.99	$15.99
02279	Foam Window Seal (Lowe's)	Seal for Enhanced Load Temperature Retention (Ross Sison's Purchase)	1	$3.48	$3.48
B077Z5FJ19	Black Electrical Tape	Holding Fluke 289 Thermocouples in Place and for Attaching Safety Notes	1	$4.98	OIT & Ross Sison Provided
B0006HV1LE	3-Ring Binder with Pockets	Holding Safety Information and Emergency Contact Information	1	$7.30	Ross Sison Provided
PVS60085MR	BK Precision High Power Programmable DC Power Supply	Programmable DC Power Supply	1	$4,090.00	OIT Provided
B07DL3MY21	Rcharlance 150A RC Watt Meter	Watt Meter and Power Analyzer	1	$14.99	OIT Provided
MNEPV20	MidNite 20A Solar Photovoltaic DC Circuit Breaker	Current Protection for PV System from the Solar Panel Module	1	$22.50	OIT Provided
JB-3960-KO	BUD Industries JB-3960-KO Steel NEMA 1 Metal Junction Box	Junction Box to House the DC Circuit Breaker	1	$22.36	OIT Provided
737123110957	Dinkle Combiner DK2.5N-BL 10 Gang Power Distribution	DIN Rail Terminal Blocks, 12-22 AWG, 20 Amp, 600V Solar Combiner	2	$14.69	OIT Provided
B079F4GC73	Electrodepot Slotted Steel Zinc Plated DIN Rail, 35 mm x 6 Inches, Silver - 2 Pieces	Slotted Steel DIN Rail for Mounting the DIN Rail Terminal Blocks	1	$8.99	OIT Provided
B01FT485S0	DIN Rail Slotted Aluminum RoHS 12" Inches Long 35mm Wide - 1 Piece	Slotted Steel DIN Rail for Mounting the DIN Rail Terminal Blocks	1	$5.29	OIT Provided
PAN F2.5X3LG6	Panduit PVC F2.5X3LG6 Type F Slotted Wall Wiring Duct - 6 Feet (2.5 Inch Width)	Wire Guiding Duct for PV System Wires	1	$21.46	OIT Provided
B000HACYOS	Primary Wire, 18-Gauge Bulk Spool, 100-Feet, Red	Red Color Code Wire for Positive Wiring	1	$8.50	OIT Provided
B003J699RW	Primary Wire, 18-Gauge Bulk Spool, 100-Feet, Black	Black Color Code Wire for Negative Wiring	1	$8.50	OIT Provided
B07FP7RRX9	XHF 22-16 AWG Female Spade Disconnect Connectors Terminals	Female Wire Connectors for DC Car Adapter Socket	1	$6.99	OIT Provided

B00EZJBELQ	Car Charger Power Female Cigarette Lighter Socket Plug Adapter	Female Cigarette Lighter Connection Port for the DC Igloo Cooler Unit	1	$7.29	OIT Provided
B01D82U3PS	22-16 Gauge Ring Insulated Electrical Wire Terminals Wire Crimp Connectors (M4, Red)	Wire Connectors for the Battery Terminals	1	$7.99	OIT Provided
B01MU0WMGT	ALLPOWERS 20A Solar Charge Controller	Charge Controller Unit	1	$18.99	OIT Provided
0161639	30A, 250V, NEMO L6-30P, 2P, 3W, Locking Plug, Industrial Grade, Grounding, BW	Materials for Connecting the DC SAS Power Supply to the OIT Power Lab Microgrid	1	$22.19	Richard Ellis Provided
0161640	30A, 250V, NEMO L6-30R, 2P, 3W, Locking Connector, Industrial Grade, Grounding, BW	Materials for Connecting the DC SAS Power Supply to the OIT Power Lab Microgrid	1	$48.83	Richard Ellis Provided
1431117	Miniature Circuit Breaker, 2-Pole, 35A, 480V/277V AC, C-Curve 10kAIC. ST200M Series. Supplemental Protection.	Materials for Connecting the DC SAS Power Supply to the OIT Power Lab Microgrid	1	$49.99	Richard Ellis Provided
0171843	(3) 10 AWG Conductors, SO/SOOW type, Copper Conductor, Stranded, Carolprene Jacket	Materials for Connecting the DC SAS Power Supply to the OIT Power Lab Microgrid	20	$1.50	Richard Ellis Provided
0387198	Stress Reducer/LEV L7504 Cord Grip	Materials for Connecting the DC SAS Power Supply to the OIT Power Lab Microgrid	1	$30.55	Richard Ellis Provided
FS-200SS PG 120.00	Slotted Standard 1-5/8" x 1-5/8" Strut Channel, Pre-Galvanized Steel, 12 ga., 10 ft.	3310T57 Strut Channel for the Main Posts of the PV Trainer Structure	4	$48.00	OIT Provided
ZB1400HS 10	10 ft. 14-Gauge Half Slotted Metal Framing Strut Channel - Gold Galvanized	3310T513 Strut Channel for the Main Posts and Structural Supports for the PV Trainer	8	$22.47	OIT Provided
B017MU06WC	HDPE (High Density Polyethylene) Plastic Sheet 1/2" x 24" x 48" Natural	Plastic Sheet Backing for Attaching the PV System Connections/Devices	2	$84.50	OIT Provided
MGUSDBA250SSS-A	5" Swivel Casters Moogiitools Red Polyurethane Wheel (4 Pack)	Wheels for the PV Trainer Cart	1	$36.99	OIT Provided
	Total Items / Costs / Team Expenses		**78**	**$8,733.53**	**$44.35**

Appendix H: Possible Idealized System

Materials

The design for the project consists of several primary components, namely: solar panel, battery storage, and the charge controller. The system was designed under the assumption that refrigeration unit would need an average power of 384 Wh/day based on the ideal refrigeration unit, the ACOPower R40A Portable Solar Fridge.

Refrigeration

Most market freezers are based on using a compressor and a refrigerant liquid to keep the interior of the cooler at temperature. This technology is commonplace throughout the world and has seen widespread success being deployed and used in the cold chain which is important when it comes to maintenance and operation. The drawback to a compressor system is the increased power draw but this is offset but the increased stability of the internal temperature which is crucial for vaccine storage. Given these tradeoffs, an ACOPower R40A Portable Solar Fridge (Fig. 15) was chosen as the ideal unit to transport polio vaccines in northern India [58].

Fig. 15: ACOPower R40A Potable Solar Fridge which has superior cooling characteristics compared to the Igloo Iceless Thermoelectric Cooler used for the SPVR unit.

This fridge was chosen due to the size, portability, and efficiency in maintaining internal temperature which would all be beneficial for deployment to Uttar Pradesh (Fig. 16).

Fig. 16: Map highlighting the area of Uttar Pradesh. (Source: Google Maps)

Battery

A battery storage system is required in a PV array when there is a need for continuous power. If the solar array is not producing electricity (nighttime hours and rainy days) there needs to be suitable energy storage to power the fridge. Due to load size and limitations on portability, a single day of autonomy was chosen for the system. This reduces the number of batteries that must be carried and the size of the solar array required. For these reasons, a ReLion RB35 12 V 35 Ah Lithium-Iron Phosphate battery was chosen (Fig. 17). One of the benefits of this lithium battery is that the phosphate replaces cobalt in a typical lithium cell, reducing the toxicity of the battery in the case of improper disposal [59]. These health risks have been noted in NHFS-4 (National Family Health Survey) report conducted by the Indian government [60]. Lithium batteries are known for higher energy density than typical Lead Acid which allows similar capacity at a reduced weight. The total weight of the battery is 9.9 lb (4.5 kg), with a nominal voltage of 12.8 V [61].

Fig. 17: RELion RB35 lithium iron phosphate battery.

Solar Panel

To power the load and to charge the batteries, the Renogy 200 W Foldable Solar Panel was chosen due to the packability of the system (Fig. 18) [62]. The foldable design allows for the system to be deployed and stored with ease and allows the system to stay mobile. Given a daily average of 4.2 peak-sun hours in Uttar Pradesh during the month of January (the lowest peak sun month) the 200 W module should be able to operate at full capacity and produce 840 Wh/day. These calculations assume an ideal tilt and zero sky cover.

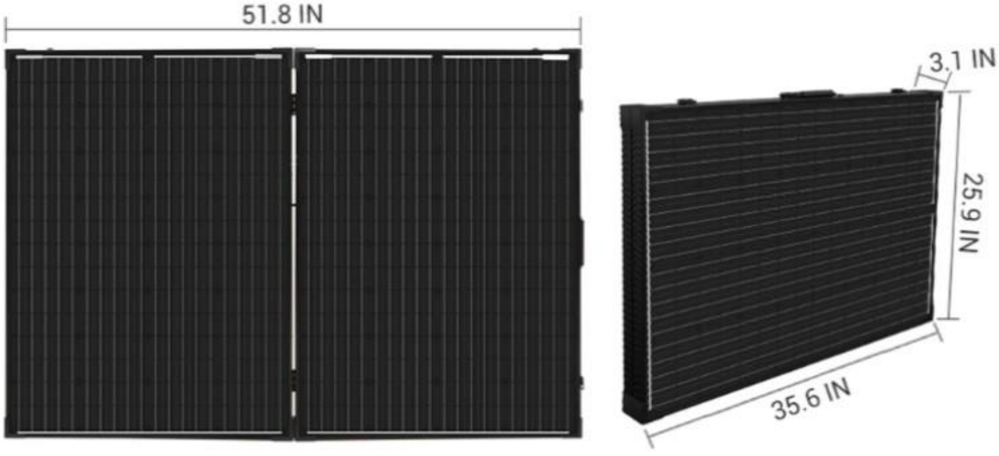

Fig. 18: Renogy 200 W Foldable Solar Panel.

Charge Controller

The central unit between the load, battery, and array is the charge controller. This device acts to balance the system and to prevent reverse current flow from the battery to the solar panel. Charge controllers come in two primary types: Pulse Width Modulation (PWM) and Max Power Point Transfer (MPPT). MPPTs are the modern standard and offer several benefits over the PWM style devices such as being able to change the voltage output of the panel to maximize the power being produced by the array and charge the battery more efficiently. The charge controller also acts to balance the system so the load (fridge) can be powered at the same time the battery is being charge allowing for uninterrupted service. A GenaSun 14.2 V MPPT Solar Charge Controller was chosen to provide optimum charging to the battery and being designed specifically for lithium iron phosphate batteries [63]. The charge controller has a high efficiency (98.3%) and a small footprint to keep the system portable.

Fig. 19: GenaSun GV-10 Lithium Iron Phosphate MPPT Solar Charge Controller.

Design Considerations

In future renditions of the SPVR unit, the solar generation and energy storage capacity of this system could possibly be expanded to account for variations in the solar radiation in Uttar Pradesh. According to the PV system calculations it would take approximately eight 100 W panels (assuming 5.72 peak amps/module) to charge a 55 Ah battery with one day of autonomy. A possible future system may include four 200 W PV panels which could recharge four, 12 V, 35 Ah Lithium batteries which would allow the SPVR unit to have approximately 2 days of autonomy. However, future designs must consider that including more generation and storage capacity would results in a higher overall system weight, size, and cost.

Appendix I: PV System Photos

Fig. 20: Igloo Iceless Thermoelectric Cooler with the vaccine vials and thermal mass (i.e., water battles) in place. The position of the water bottles conforms to the CDC standards for refrigerated vaccines and the standards for packing vaccines for transport in emergency situations.

Fig. 21: Top-down view of plastic basket that holds the vaccine vials. Beneath this container is a row of five water bottles that act as the thermal mass (for the lower portion of the cooler).

Fig. 22: Complete SPVR unit while the second 48-hour system test was in progress.

Appendix J: Table of Parameters Tested for the Experiment

TABLE XII: Summary of variables and parameters that the team focused on testing for this project.

Measure (Y-Axis)	Independent Variable (X-Axis)	Parameters to Hold Constant	Equipment to Use
Load Voltage Draw	Time	ALL*	Power Meter
Load Current Draw	Time	ALL*	Power Meter
Load Power Draw	Time	ALL*	Power Meter
Interior Temperature & Humidity of Fridge	Time, Battery Charge	ALL*	Thermocouple, PUSH temperature sensor, or Hygrometer
Interior Temperature & Humidity of Fridge	Time, Battery Charge	POWER OFF CONDITION	Thermocouple, PUSH temperature sensor
Exterior Temperature & Humidity of Fridge	Time	ALL*	Temperature Sensor
Interior Temperature Tolerance (for DC/AC Thermostat Probe)	Time	ALL*	DC Thermostat, PUSH temperature sensor +
Interior Humidity Tolerance (Difference between sensors)	Time	ALL*	Hygrometers (dedicated device or integrated w/ temperature sensors)
Battery Voltage and Current Output (Full Charge)	Discharge Time (to rated Depth of Discharge), Ambient Temperature	NO SOLAR INPUT*	Power Meter, Thermocouple, PUSH temperature sensor
Charge Controller Output Power	Time	ALL*	Power Meter, Digital Multimeter

*_ALL (unless otherwise noted in the independent variable column): Temperature, Brightness (Intensity), Humidity, Ambient Conditions, Wind, Electrical and Magnetic Interference is assumed to Negligible

Appendix K: Basis for the Second 48-Hour Test DC SAS Parameters

Given: The solar radiation for a particular location is (3350 Wh/m^2)/day. A solar panel that is 0.736 square meters and is rated at 100 Wh (peak output) is used. Assume that the peak solar radiation under ideal conditions to be 1000 Wh/m^2.

Find: The energy output per day in (Wh/day) for this solar panel.

Solution Approach

(455 Wh/m^2)/day assumes that 13.95% (of the locational solar radiation) is the hypothetical value if the solar panel itself had 1 square meter (of solar cells). The panel is rated at 100 W, under peak conditions of 100 Wh/m^2, the energy output is 100 W or 10%. 10% of 3350 W is 335 W.

In the first calculation below, the team multiplied the solar radiation of Allahabad with 13.95% or ((135.9 Wh/m^2)/(1000 Wh/m^2)). Then, the team multiplied this value with the area of the solar panel which tailors the calculation specifically to the size of the solar panel. This also cancels the sq. meters term.

$$\frac{3350\,Wh}{\frac{m^2}{day}} * \frac{\frac{135.9\,Wh}{m^2}}{\frac{1000\,Wh}{m^2}} * \frac{0.736\,m^2}{1 panel} = \frac{335\,Wh}{day}$$

If we want this result to be in terms of W/day, we must include the conversion (1 day/1 hour) assuming that all the solar radiation of the day was placed in one hour. This cancels the (h) and (day) units to provide W/day.

$$\frac{3350\,Wh}{\frac{m^2}{day}} * \frac{\frac{135.9\,Wh}{m^2}}{\frac{1000\,Wh}{m^2}} * \frac{0.736\,m^2}{1 panel} * \frac{1\,day}{1\,hour} = \frac{335\,Wh}{day}$$

Solution: The solar panel's energy output would be 335 Wh/day or 335 W/day. Fig. 23 shows the programming approach for the DC SAS PS.

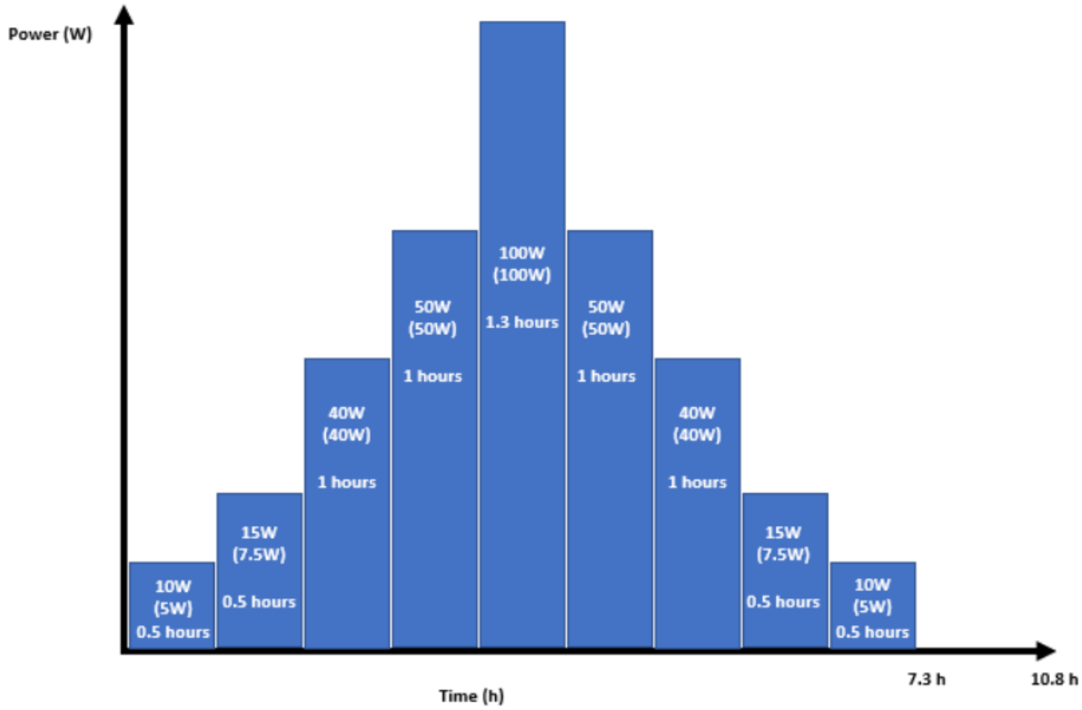

Fig. 23: Planned power input program for the DC SAS Power Supply for second 48-hour test. Please note that the position of the time marks on the x-axis are not to scale.

Given:
100-Watt Panel
18.9 V (Optimal)
5.29 A (Optimal)
Assumptions:
335 Watts per Day
Graph Information:
- Values in parenthesis are the total Watts in that interval of time
- Values not in parentheses are the wattage outputs of the panel during that time interval
- The total area of the bar graph is equal to the total power output of the panel per day
- The suggested voltages and amperage for each bar could be:

100 W (18.9 V, 5.29 A)
50 W (13.36 V, 3.74 A)
40 W (11.95 V, 3.35 A)
15 W (7.32 V, 2.05 A)
10 W (5.98 V, 1.67 A)
- The voltages and currents were based on the formulae:

$$P = xV * xI$$

$$x = \sqrt{\frac{P}{(18.9\,V)(5.29\,A)}}$$

where *x* is a constant and *P* is the desired power output.

Appendix L: Estimated Dimensions of Selected Main PV System Components

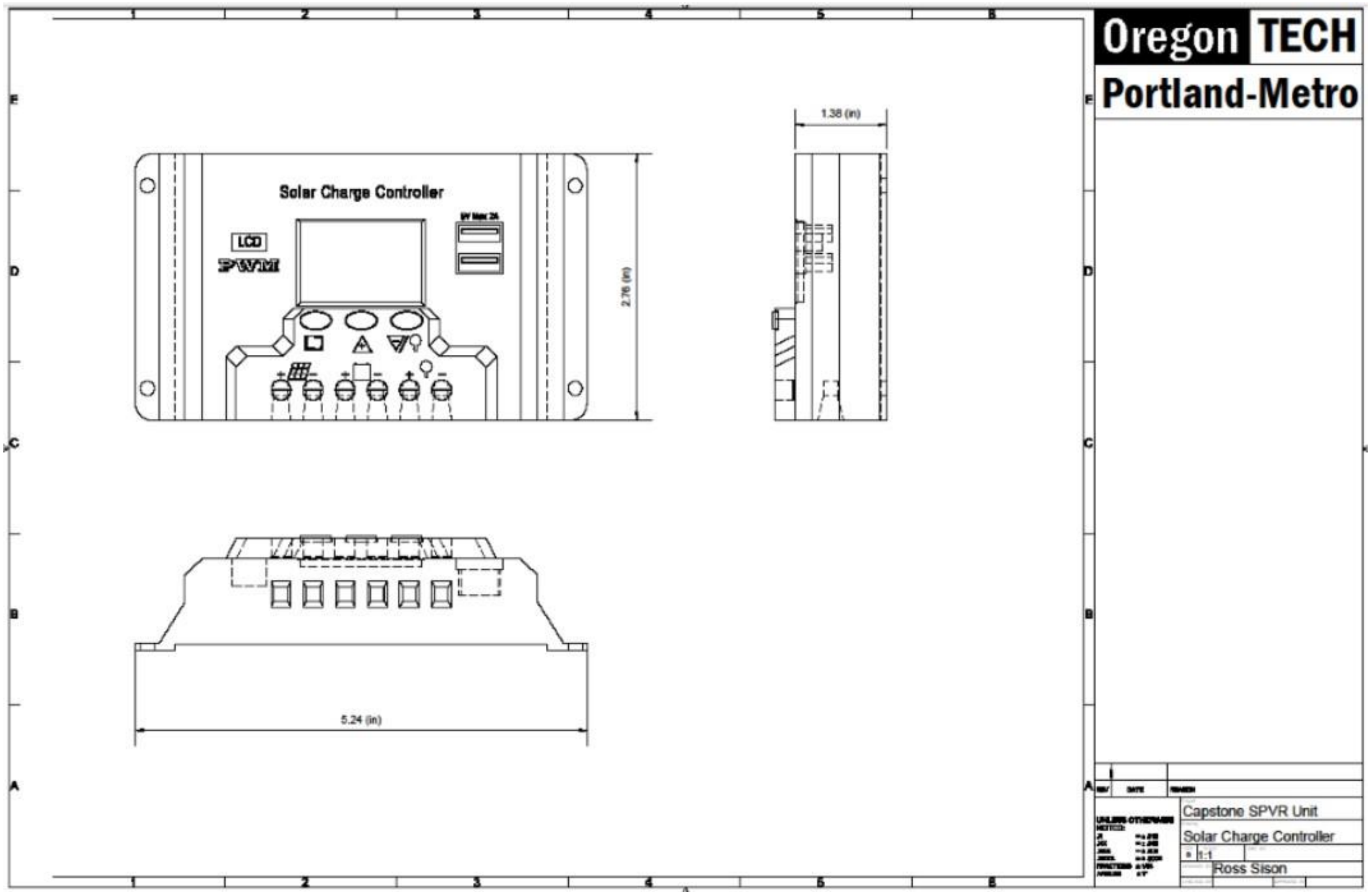

Fig. 24: Fusion 360-generated drawing of the ALLPOWERS charge controller used in all full-SPVR system tests.

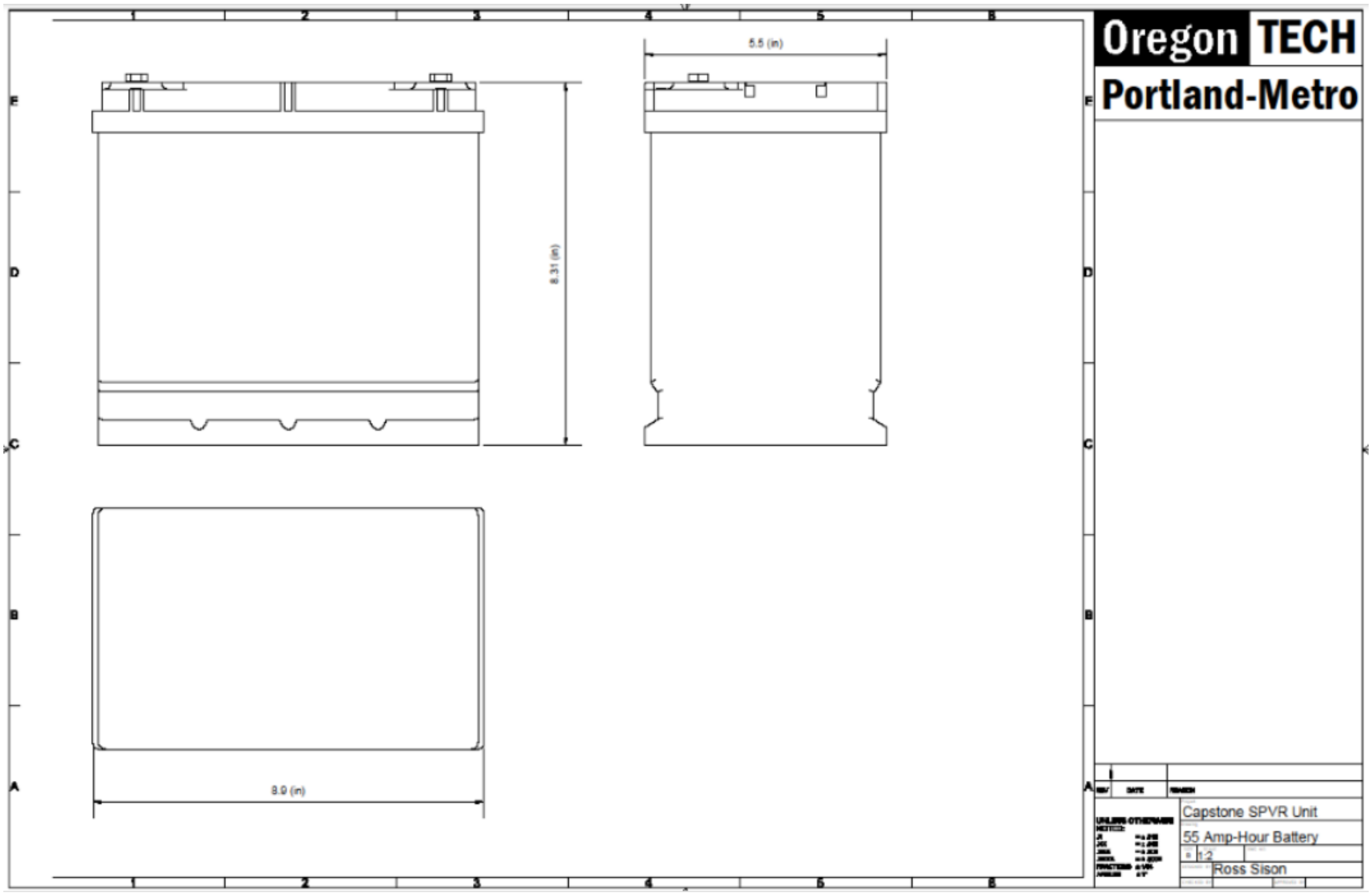

Fig. 25: Fusion 360-generated drawing of ExpertPower, 55 Ah, 12 V battery unit used for battery discharge and all full-SPVR system tests.

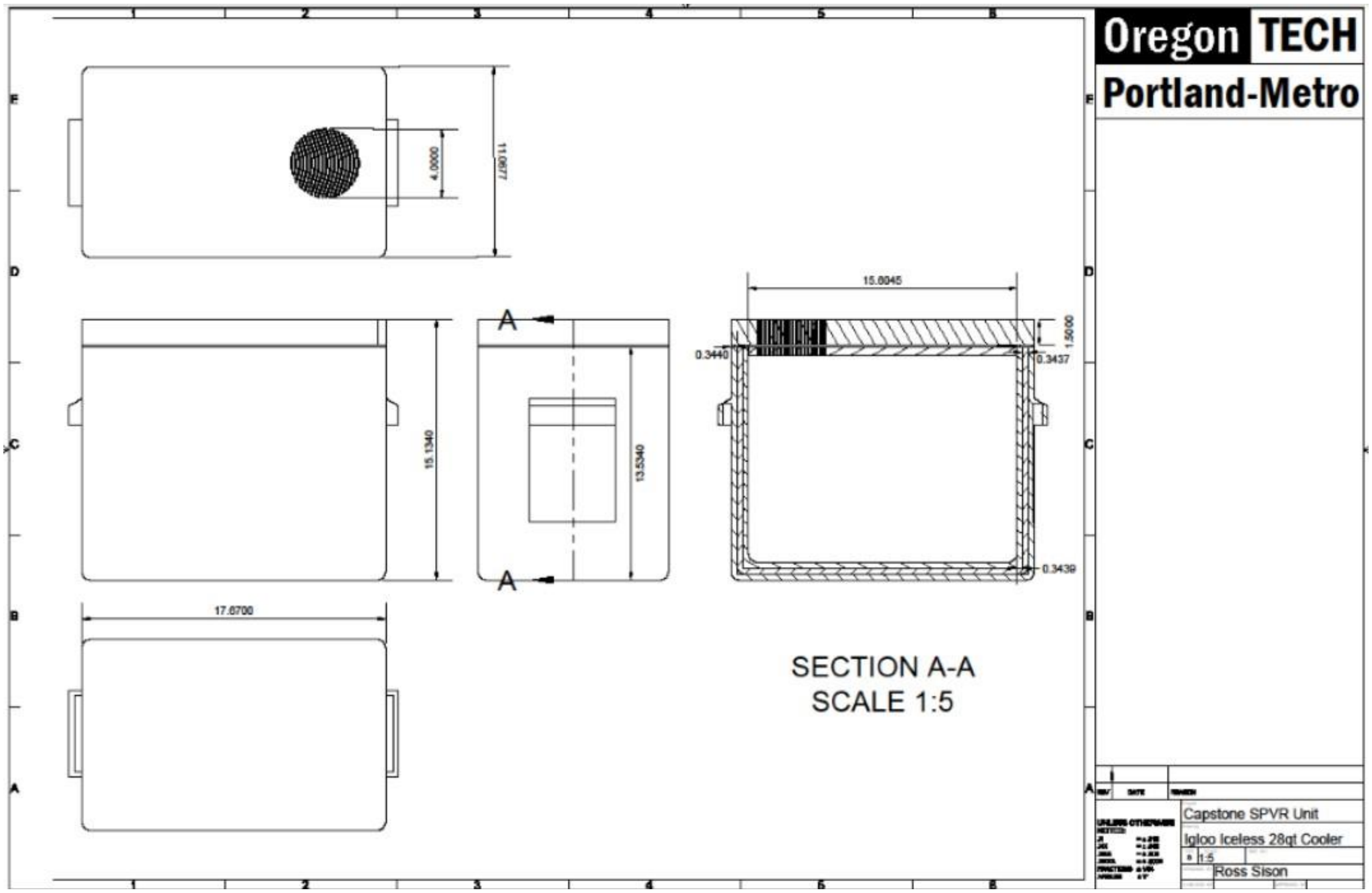

Fig. 26: Fusion 360-generated drawing of the Igloo Iceless 28-quart Thermoelectric Cooler. Please note that the dimensions of the cooler are inaccurate by approx. 3 in due to the challenges faced in modeling the curved edges of this unit to match the actual product specifications.

The actual dimensional information of the TEC unit (shown in Fig. 37) is provided below for reference:

- Length 19.12 in
- Width 13.25 in
- Height 18.31 in
- Link https://www.walmart.com/ip/Igloo-28-Qt-Iceless-Cooler-in-Silver/34053000

Appendix M: Project Testing Procedures

<u>*LOAD TEST I – PRELIMINARY TEMPERATURE AND HUMIDITY MEASUREMENTS*</u>

1. Check the physical condition of the fridge and connections.
2. Set up the PUSH temperature sensors on the upper and lower portions of the cooler and connect them to the phone.
3. Place two Fluke 289 meters to record the heat sink temperature and the temperature at the side of the cooler.
4. Place an emergency ambient temperature sensor near the cooler.
5. Close the cooler lid and make sure that it is firmly shut.
6. Review the relevant LOTO and re-energization procedures outlined in the Safety Binder.
7. Plug the Igloo cooler to the AC thermostat controller using the DC adapter provided.
8. Plug the AC Thermostat Controller into the wall outlet.
9. Set the AC thermostat controller between 2°-8 °C.
10. Record the initial temperature and humidity readings of all sensors.
11. Record all temperature and humidity readings every 15 minutes for approximately 8-9 hours.
12. Take photos of the setup.
13. Remove the power cord to the fridge.
14. Remove the AC thermostat controller from the wall output and leave the PUSH sensors in the cooler for Load Test II.
15. Follow the relevant LOTO and de-energization procedures outlined in the Safety Binder

16. Complete and file safety checklists.

LOAD TEST II – TEMPERATURE, HUMIDITY, and AC POWER DRAW (WITH THERMAL MASS)

1. Check the physical condition of the fridge and connections.
2. Set up the two FLUKE 289 temperature sensors on the upper and lower portions inside the cooler.
3. Place two PUSH sensors to record the heat sink temperature and the ambient temperature one foot from the side of the cooler with the heat sink. Ensure connection to a phone.
4. Place an emergency ambient temperature sensor near the cooler.
5. Close the cooler lid and make sure that it is firmly shut.
6. Review the relevant LOTO and re-energization procedures outlined in the Safety Binder.
7. Plug the AC Thermostat Controller into the wall outlet.
8. 8. Note where the temperature remained consistent during Load Test I and use this at the low point (LP) for the AC thermostat controller setting.
9. Set the AC thermostat controller between (LP Value) - 8 °C.
10. Record the initial temperature and humidity readings of all sensors.
11. Plug the Igloo cooler to the power meter.
12. Plug the power meter to the AC thermostat controller using the DC adapter provided.
13. Record all temperature and humidity sensor readings every 15 minutes for 8-9 hours or until a stable temperature has been reached by the cooler for approximately 1 hour.
    i. When the temperature of the cooler has reached 8 °C, place the thermal mass (30-35 frozen vaccine vials and 4 frozen water bottles) into the fridge.
14. Take photos of the interior and exterior of the setup.
15. Remove the power cord to the fridge.
16. Remove the AC thermostat controller from the wall output and leave the PUSH sensors in the fridge for Load Test III.
17. Follow the relevant LOTO and de-energization procedures outlined in the Safety Binder
18. Complete and file safety checklists.

LOAD TEST III – TEMPERATURE, HUMIDITY, and AC POWER DRAW (WITH THERMAL MASS): SIMULATED APPLICATION OF VACCINE COOLING

PART I: VACCINE VIAL PREPARATION

1. Measure and record the weight of one vaccine vial.
2. Fill a 250 ml beaker with tap water.
3. Add 20 g of salt and mix for 30 seconds.
4. Add 20 ml to water to 15 glass vials.
5. Repeat steps 2-4 until 40-45 glass vials have been filled.
6. Label all the glass vials with water with the following information.
    i. Abbreviated Name of Capstone Project
    ii. Class Name (ENGR 465)
    iii. Contents of the Vial
    iv. Contact Information
7. Obtain and fill 10 water bottles with 500 ml of water.
8. Label all the water bottles with the following information.
    i. Abbreviated Name of Capstone Project
    ii. Class Name (ENGR 465)
    iii. Contents of the Bottle
9. Fill and 8 liquid-storage containers that are 200 ml or larger.
10. Label all the containers with the following information.
    i. Abbreviated Name of Capstone Project
    ii. Class Name (ENGR 465)
    iii. Contents of the Bottle
11. Take photos of all vials and water containers.
12. Store all vials and water bottles in a refrigerator at least 24 hours before Part II.
13. Take photos of the storage space (of the refrigerator).
14. Obtain the following dimensional measurements for the cooler.
    i. Thickness of cooler walls, cover, and cooling unit

ii. Length and Width of bottom & top portion of the cooler

15. Take photos of the cooler and label the cooler with the measured dimensions.
16. Build a Vaccine Rack with the following characteristics
    i. Must be able to stack on top of water bottles that are horizontally positioned
    ii. Must be capable of having water bottles stacked on top of the rack

PART II: MEASUREMENT EQUIPMENT PREPARATION

1. Check the physical condition of the fridge and connections.
2. Place an adhesive foam seal on the bottom rim of the fridge and create small slits to allow for the passage of the wires in the front.
3. Set up the two FLUKE 289 temperature sensors on the upper internal portion, lower internal portion, and heat sink of the cooler. Make sure that one of the sensors is dedicated for the vaccine vials.
    i. Ensure that all wires coming out of the cooler must exit the front of the cooler (and not near any hinge).
4. Place two PUSH sensors to record the heat sink temperature and the temperature at exactly 12 inches from the side of the cooler.
    i. Ensure Wi-Fi/Bluetooth connection to a phone with the PUSH sensor application.
5. Place an emergency ambient temperature sensor near the cooler.
6. Set up the sensor of the AC Thermostat Controller and ensure that the probe wire comes out of the front portion of the cooler.
7. Take photos of the interior and exterior setup.

PART III: COOLER PREPARATION

1. Close the cooler lid and make sure that it is firmly shut.
2. Review the relevant LOTO and re-energization procedures outlined in the Safety Binder.
3. Plug the AC Thermostat Controller into the wall outlet.
4. Set the AC thermostat controller to –10 °C to force the cooler to continuously work.
5. Record the initial temperature and humidity readings of all sensors.
6. Plug the Igloo cooler to the power meter. Make sure that the cooler is connected firmly into the AC power adapter.
7. Place 8 of the frozen water containers in the cooler.
8. Record all temperature and humidity sensor readings every 15 minutes for a set period decided by the group. This time period will be determined by the temperature trends for the cooler.
9. When the temperature of the top and bottom portions of the cooler are at (or below) 8 °C, take photos of the exterior setup and proceed to Part IV.

PART IV: THERMAL MASS INCLUSION AND MEASUREMENT

1. Prepare and agree on which member of the group will execute the following tasks:
    i. Opening and closing the fridge
    ii. Preparing the Vaccine Rack
    iii. Placing of water bottles
2. The following tasks below should be done within the span of 5 minutes.
3. Obtain the refrigerated vials and water bottles.
4. Place 40-45 vaccine vials in the container and take a photo of the setup.
5. Place 5 of the 500 ml water bottles on the bottom of the fridge and take a photo.
6. Place the vaccine vial rack on top of the water bottles and take a photo
7. Place the other 5 of the 500 ml water bottles on the top of the vial rack and take a photo of the setup.
8. Close the cooler door and ensure that it is shut.
9. Record all temperature and humidity sensor readings every 15 minutes for 24 Hours.
10. Take photos of the setup.
11. Once the temperature and power measurements have been obtained, be sure to remove the power cord to the fridge.
12. Remove the AC thermostat controller from the wall output and extract the PUSH sensors (unless they will be used for another test).
13. Follow LOTO and de-energization procedures outlined in the Safety Binder.
14. Complete and file safety checklists.

BATTERY DISCHARGE TESTING 1 - USING DC SIMULATED POWER SUPPLY ONLY

1. Ensure that there are no connections to the terminals of the battery
2. Ensure that the battery is charged to the nominal battery voltage level (at float charge).
3. Connect the Fluke 289 (set to measure Voltage) in parallel to the terminals of the battery.
4. Connect the terminals of the DC Load Simulator to the proper terminals of the battery.
5. Set the DC Load Simulator to consume V = 12 V and I = 4.8 A (simulating the rated nominal high-power consumption of an Igloo 28-quart cooler).
6. Follow LOTO and re-energization procedures as outlined in the Safety Binder before activating the DC Load Simulator.
7. Take photos of the setup.
8. Check the voltage level on the Charge Controller 3-5 times in a 24-hour period to see whether the battery has reached the maximum depth of discharge (or approximately 10.8 Volts).
9. Once the charge controller shuts off or reaches the lowest recommended DOD, turn off the DC Load Simulator.
10. Follow LOTO and de-energization procedures outlined in the Safety Binder.
11. Complete and file safety checklists.
12. Recharge the battery using the Duracell Battery Recharger.

PV SYSTEM and LOAD PERFORMANCE TESTING GUIDE – USING DC SIMULATED SOLAR POWER SUPPLY ONLY

This will be the procedure that will be used for all full PV system tests.

1. Ensure that all PV system connections are correctly placed.
2. Ensure that the PV module is connected correctly to the controller.
3. Ensure that the DC thermostat controller is connected correctly to the load port. Set the operating temperature range to 2°-8 °C.
4. Ensure that the battery is connected correctly to the charge controller.
5. Verify that the charge controller is functioning and set the charge controller to have a low voltage disconnect of 11.6 Volts.
6. Check the physical condition of the fridge and connections.
7. Set up three Fluke 289 sensors in the following positions:
   a. Battery Voltage (i.e., parallel connection with battery)
   b. Input Current to Cooler (i.e., in series with the DC power port of the cooler)
   c. Vaccine-level of the cooler
8. Set the sensors to record for a 24 or 48-hour period depending on the type of test.
9. Review the LOTO and re-energization procedures outlined in the Safety Binder.
10. Set the DC simulated solar power supply to use the preset PV SIM CURVE or program a PV curve as required by the project testing parameters.
    a. Prepare and agree on which member of the group will execute the following tasks:
       i. Opening and closing the fridge
       ii. Preparing the Vaccine Rack
       iii. Placing of water bottles
    b. The following tasks below should be done within the span of 5 minutes.
    c. Obtain the refrigerated vials and water bottles.
    d. Place 40-45 vaccine vials in the container and take a photo of the setup.
    e. Place five of the 500 ml water bottles on the bottom of the fridge and take a photo.
    f. Place the vaccine vial rack on top of the water bottles and take a photo.
    g. Place the other five 500 ml water bottles on the top of the vial rack and take a photo of the setup.
    h. Close the cooler door and ensure that it is shut.
11. Take photos of the setup.
12. Set the DC simulator solar power supply to the ON status.
13. Start the recording for the Fluke 289 sensors and monitor the following items for the set duration of the test (24-hours or 48-hours)
    a. Temperature and Humidity of the Fridge 3-5 times per day (e.g. 8am, 12pm, 4pm) according to the CDC Vaccine Storage and Handling Toolkit guide (https://bit.ly/2RxOKM9).
    b. Voltage and Current Readings (stored electronically through the power logger)
    c. Visual checks on system performance – heat, sound, safety checks (i.e., when any available group members have the chance to check the system). These checks must be carried out at least 3-5 times during the duration of the test.
14. Once all recording objectives have been completed, turn OFF the DC simulated solar power supply and the Fluke 289 devices.

15. Follow the relevant LOTO and de-energization procedures outlined in the Safety Binder.
16. Complete and file safety checklists.

Appendix N: Project Testing Parameters

TABLE XIII: Parameter list for the first load test performed on the thermoelectric cooler.

Load Test 1
Date: 01/30/2020
Start Time: 9:55
End Time: 18:40
Cooler OFF: 18:25
Duration: 8 Hours 45 Minutes
Recording Interval: 15 Minutes
Thermostat Setting: 2°C-8°C
Measurement Focus:
>> Bottom of Cooler
>> Top of Cooler
>> Ambient Temperature

TABLE XIV: Parameter list for the second load test performed on the thermoelectric cooler.

Load Test 2
Date: 02/06/2020
Start Time: 10:15
End Time: 19:30
Duration: 9 Hours 15 Minutes
Thermostat Setting: 5.8°C-8°C
Recording Interval: 15 Minutes
Cooler ON: Constant
Thermal Mass Insertion: 14:40
Vaccine Vials: 31 Vials
Addl. Thermal Mass: 4 Bottles
Measurement Focus:
>> Bottom of Cooler
>> Top of Cooler
>> Ambient Temperature
>> TEC Heat Sink Temperature

TABLE XV: Parameter list for the third load test performed on the thermoelectric cooler.

Load Test 3
Date: 02/13/2020
Cooler Start: 9:50
Thermal Mass Insertion: 10:05
Start Time: 10:47
Cooler OFF: 16:50
End Time: 10:47 (next day)
Duration: 24 Hours
Thermostat Setting: 2°C-8°C
Recording Interval: 15 Minutes
Vaccine Vials: 41 Vials
Addl. Thermal Mass: 10 Bottles
Measurement Focus:
>> Bottom of Cooler
>> Top of Cooler
>> Vaccine Vials
>> Ambient Temperature
>> TEC Heat Sink Temperature

TABLE XVI: Parameter list for the battery discharge test.

Battery Discharge Test
Date: 02/20/2020
Start Time: 17:32
End Time: 11:01 (next day)
Duration: 17 Hours 29 Min.
DC Load Settings: 12V, 4.8A
Recording Interval: 15 Min.
Max. Battery Temp.: 39.44°C
Discharge Rate: Constant
Measurement Focus:
>> Battery Voltage

TABLE XVII: Parameter list for the 24-hour full SPVR system test.

24-Hour Full PV System Test
Date: 2/26/2020
Start Time: 14:46
End Time: 14:46 (next day)
Duration: 24 Hours
Thermostat Setting: 2°C-8°C
Recording Interval: 15 Minutes
Cooler Contents: 41 Vials, 10 Bottles (Thermal Mass)
Charge Controller Low Voltage Disconnect: 10.8V
PV Curve: Preset EN50530 Standard
Measurement Focus:
>> Battery Voltage
>> Current Input to Cooler
>> Vaccine Vial Temperature

TABLE XVIII: Parameter list for the first 48-hour full SPVR system test.

48-Hour Full PV System Test 1						
Date: 02/27/2020						
Start Time: 17:19						
End Time: 17:19 (next day)						
Duration: 24 Hours						
Thermostat Setting: 2°C-8°C						
Thermostat Correction: 3.8°C						
Correction Basis: Fluke 289 Vaccine Vial Sensor						
Recording Interval: 15 Minutes						
Cooler Contents: 41 Vials, 10 Bottles (Thermal Mass)						
Charge Controller Low Voltage Disconnect: 11.6V						
PV Curve: Manually Programmed						
Measurement Focus:						
>> Battery Voltage						
>> Current Input to Cooler						
>> Vaccine Vial Temperature						
PV Curve Program Data						
Step	**Start Time (h)**	**End Time (h)**	**Duration (h)**	**Voltage (V)**	**Current (A)**	**Program**
1	0	1.35	1.35	0	0	OFF
2	1.35	2.7	1.35	9.95	2.645	ON
3	2.7	4.05	1.35	13.362	3.74	ON
4	4.05	5.4	1.35	16.367	4.58	ON
5	5.4	6.75	1.35	18.9	5.29	ON
6	6.75	8.1	1.35	16.367	4.58	ON
7	8.1	9.45	1.35	13.362	3.74	ON
8	9.45	10.8	1.35	9.95	2.645	ON
9	10.8	12.45	1.65	0	0	OFF
10	12.45	14.1	1.65	0	0	OFF
11	14.1	15.75	1.65	0	0	OFF
12	15.75	17.4	1.65	0	0	OFF
13	17.4	19.05	1.65	0	0	OFF
14	19.05	20.7	1.65	0	0	OFF
15	20.7	22.35	1.65	0	0	OFF
16	22.35	24	1.65	0	0	OFF
17	N/A	N/A	N/A	N/A	N/A	REPEAT 1X

TABLE XIX: Parameter list for the second 48-hour full SPVR system test.

48-Hour Full PV System Test 2						
Date: 03/05/2020						
Start Time: 17:11						
End Time: 17:11 (next day)						
Duration: 24 Hours						
Thermostat Setting: 2°C-8°C						
Thermostat Correction: 3.8°C						
Correction Basis: Fluke 289 Vaccine Vial Sensor						
Recording Interval: 15 Minutes						
Cooler Contents: 41 Vials, 10 Bottles (Thermal Mass)						
Charge Controller Low Voltage Disconnect: 11.6V						
PV Curve: Manually Programmed						
Measurement Focus:						
>> Battery Voltage						
>> Current Input to Cooler						
>> Vaccine Vial Temperature						
PV Curve Program Data						
Step	**Start Time (h)**	**End Time (h)**	**Duration (h)**	**Voltage (V)**	**Current (A)**	**Program**
1	0	0.5	0.5	5.98	1.67	ON
2	0.5	1	0.5	7.32	2.05	ON
3	1	2	1	11.95	3.35	ON
4	2	3	1	13.36	3.74	ON
5	3	4.3	1.3	18.9	5.29	ON
6	4.3	5.3	1	13.36	3.74	ON
7	5.3	6.3	1	11.95	3.35	ON
8	6.3	6.8	0.5	7.32	2.05	ON
9	6.8	7.3	0.5	5.98	1.67	ON
10	7.3	8.95	1.65	0	0	OFF
11	8.95	10.6	1.65	0	0	OFF
12	10.6	12.25	1.65	0	0	OFF
13	12.25	13.9	1.65	0	0	OFF
14	13.9	15.55	1.65	0	0	OFF
15	15.55	17.2	1.65	0	0	OFF
16	17.2	18.85	1.65	0	0	OFF
17	18.85	20.5	1.65	0	0	OFF
18	20.5	22.15	1.65	0	0	OFF
19	22.15	24	1.85	0	0	OFF
20	N/A	N/A	N/A	N/A	N/A	REPEAT 1X

TABLE XX: Summary of Results from full SPVR system tests.

Description of SPVRU System Test	Max Time Battery Powered the Load (Operation Time in Hours)	Max Load Current During Period (A)	Average Load Current During Battery (A)	Battery Voltage at Period Start (V)	Battery Voltage at Period End (V)	Time of Power Supplied Cycle (Hours)	Total Power Supplied by the TEC During ON Cycle (W)
24-Hour Test	24	4.8	4.8	12.33	11.7	-	-
48-Hour Test (1)	12	4.4	3.8	12.7	7.8	9.45	402
48-Hour Test (2)	8	4	3.6	12.4	8.6	7.3	330

Appendix O: Project Safety Information

CAPSTONE GROUP SAFTEY AGREEMENT AND COMPLIANCE (FALL 2019 RBC PROPOSAL)

"One potential concern is that of electrical shock from exposure to hazardous current levels. This is always a risk anytime one deals with electrified equipment. All of the members of our capstone group have taken Electrical Power (REE 243) and have knowledge and experience regarding the safe handling of electrical equipment. We have successfully taken and passed the Electrical Safety Test under the Laboratory Safety Training section on Blackboard (during Spring 2019 term). We will mitigate this risk by using the Lock-Out-Tag-Out procedures as prescribed by NECA based on Article 120 of the NFPA 70E requirements. This includes disconnecting all power sources to components/devices during the construction of our electrical circuits and only supplying them with power when testing is required (once everything is properly connected). We will also perform the Re-energizing of Machine/Equipment procedure when connecting or turning on any power source. We will have a binder which includes a checklist of the LOTO procedures, Re-energizing procedures, and instructions for emergency situations which will include contacts for the group. Our project material sets and binders will be labeled as 'Solar-Powered Vaccine Refrigeration Unit (or SPVRU)'. In terms of the project materials, some of the items in our materials list are UL listed (e.g. wires and solar array) which conform with the UL safety standards (Appendix B). There is also the possibility of personal injury due to improper lifting of heavy materials. This risk will be mitigated using proper lifting techniques as well as team lifting for heavier items. Safety equipment (i.e., straps and harnesses) will be used to reduce the risk of personal injury."

Appendix P: Fusion 360 Cooler Modeling and Thermal Simulation Results

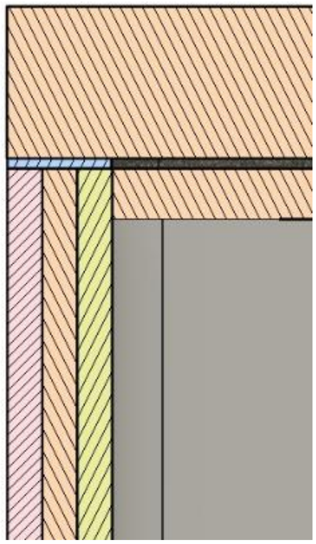

Fig. 27: Cross section of the thermoelectric cooler. From left to right: polypropylene exterior, polyurethane foam, polypropylene interior.

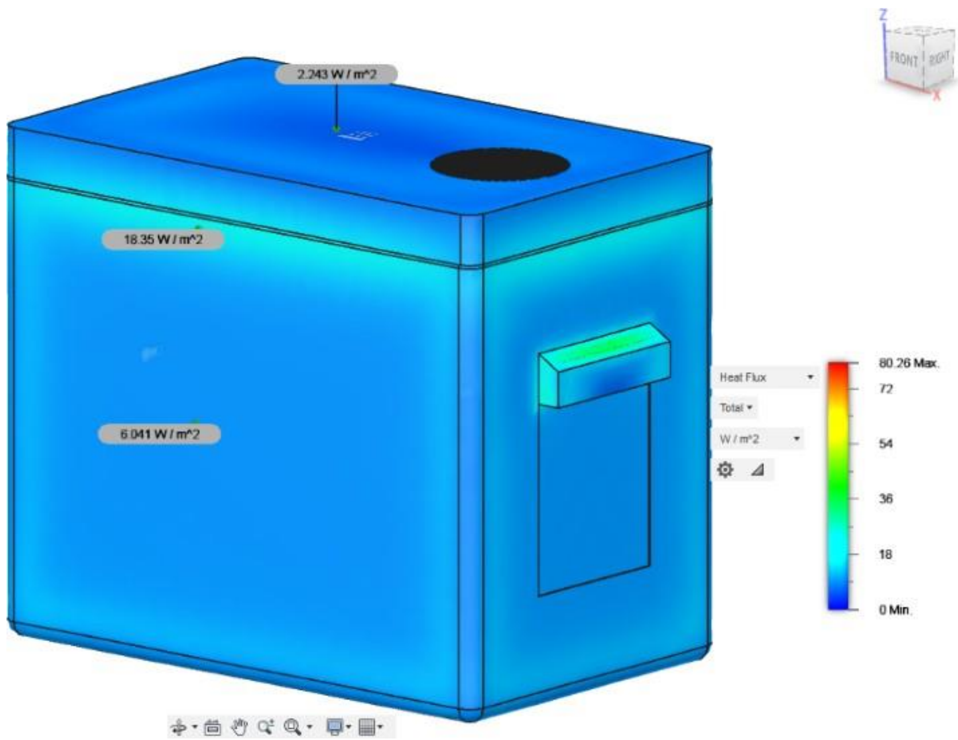

Fig. 28: Thermal simulation (Load 1) showing magnitude of heat flux through exterior wall of cooler assuming indoor temperature conditions.

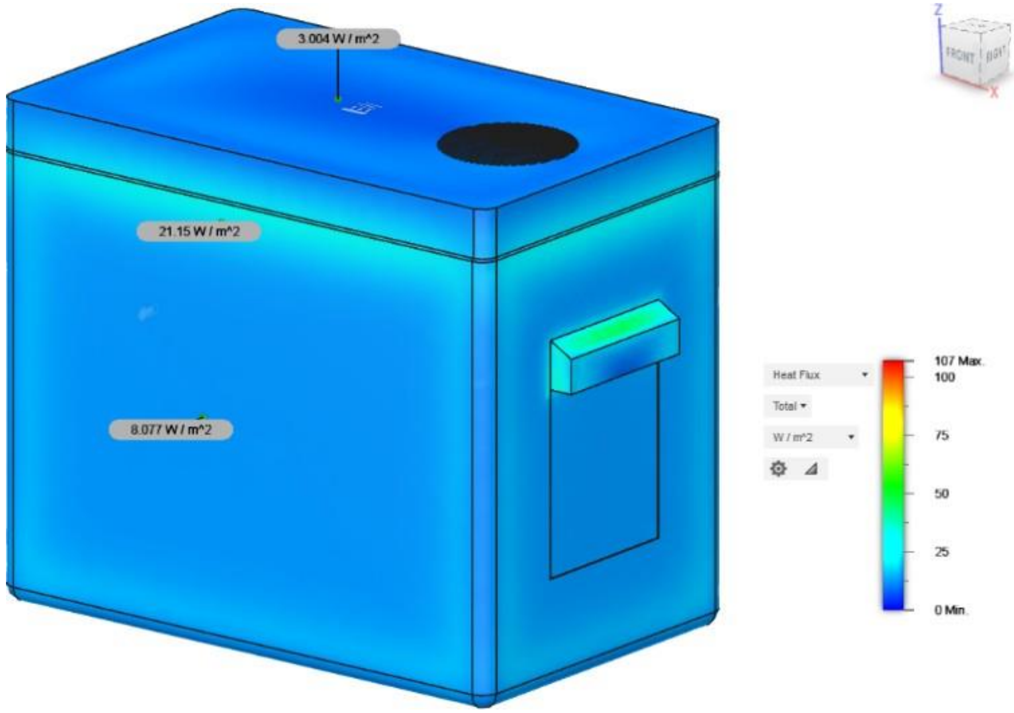

Fig. 29: Thermal simulation (Load 2) showing magnitude of heat flux through exterior walls of cooler assuming maximum ambient operating temperature conditions.

Appendix Q: Graphical Results for Load Tests, Battery Tests, and Full SPVR System Tests

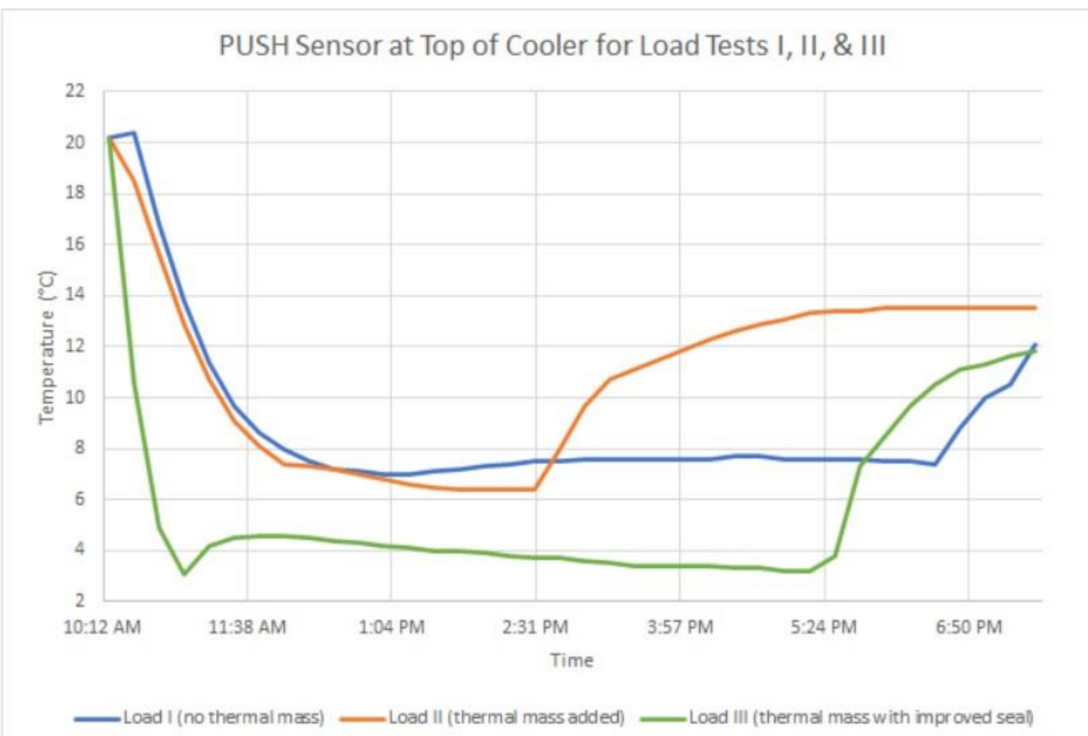

Fig. 30: PUSH sensor temperature measurements for interior ceiling of thermoelectric cooler for load tests 1-3.

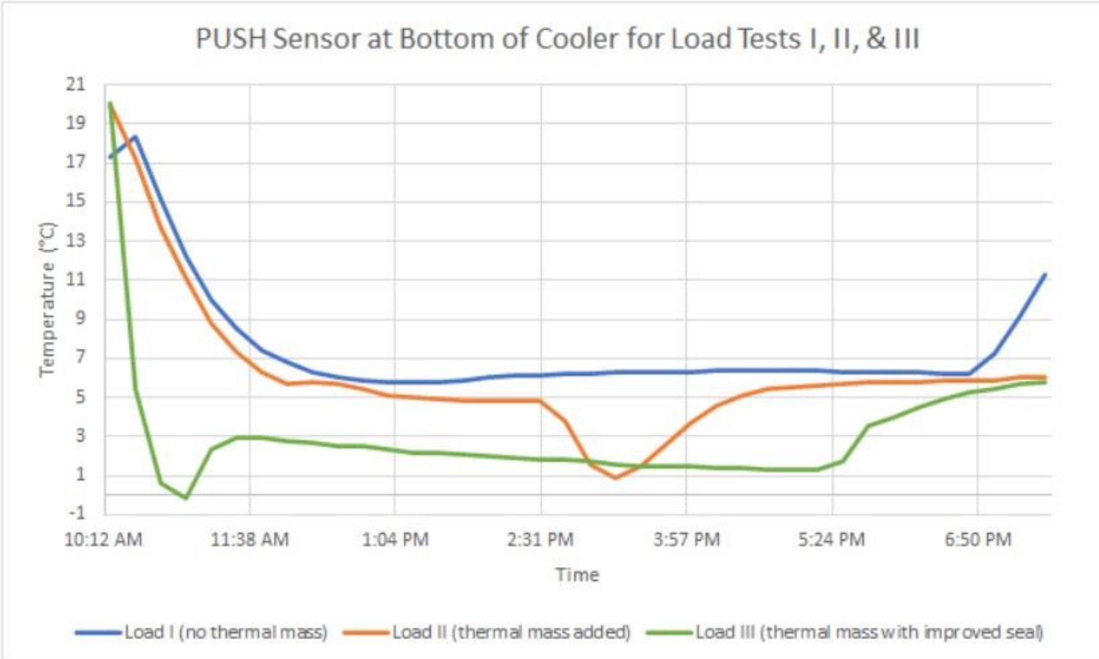

Fig. 31: PUSH sensor temperature measurements for bottom interior of thermoelectric cooler for load tests 1-3.

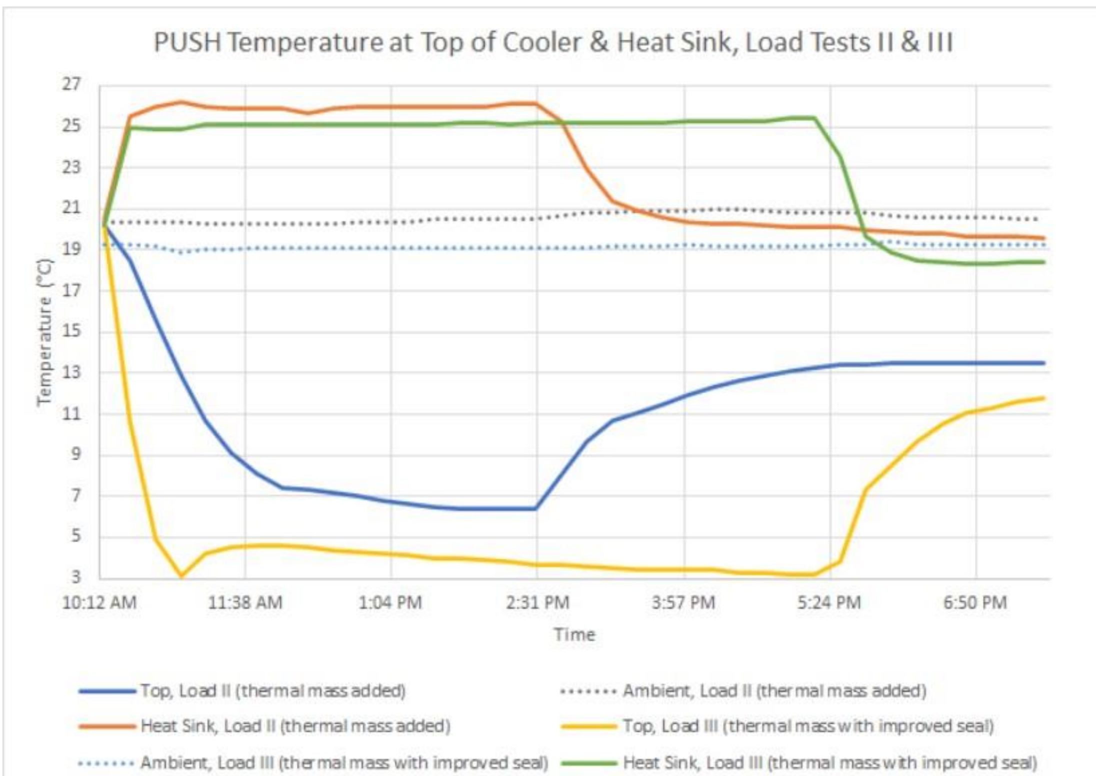

Fig. 32: PUSH sensor temperature measurements at interior ceiling and external heat sink of thermoelectric cooler during load tests 1-3.

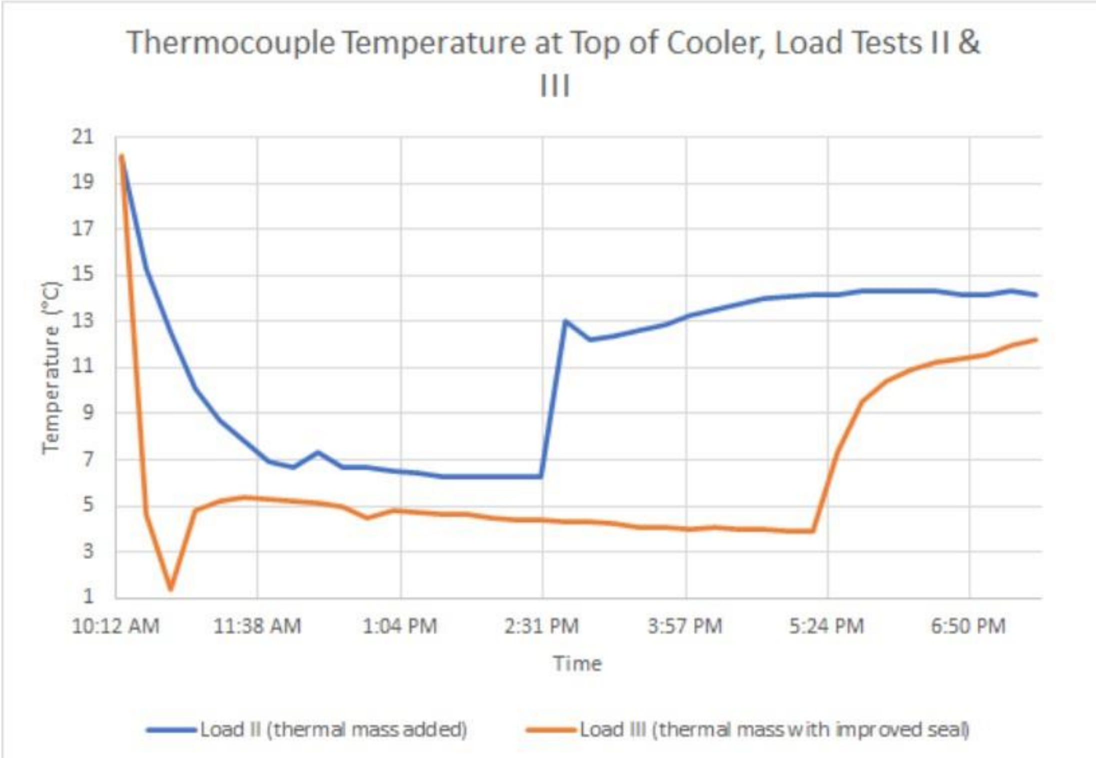

Fig. 33: Fluke 289 Thermocouple Temperature Sensor measurements at the interior ceiling of thermoelectric cooler for load tests 2 and 3.

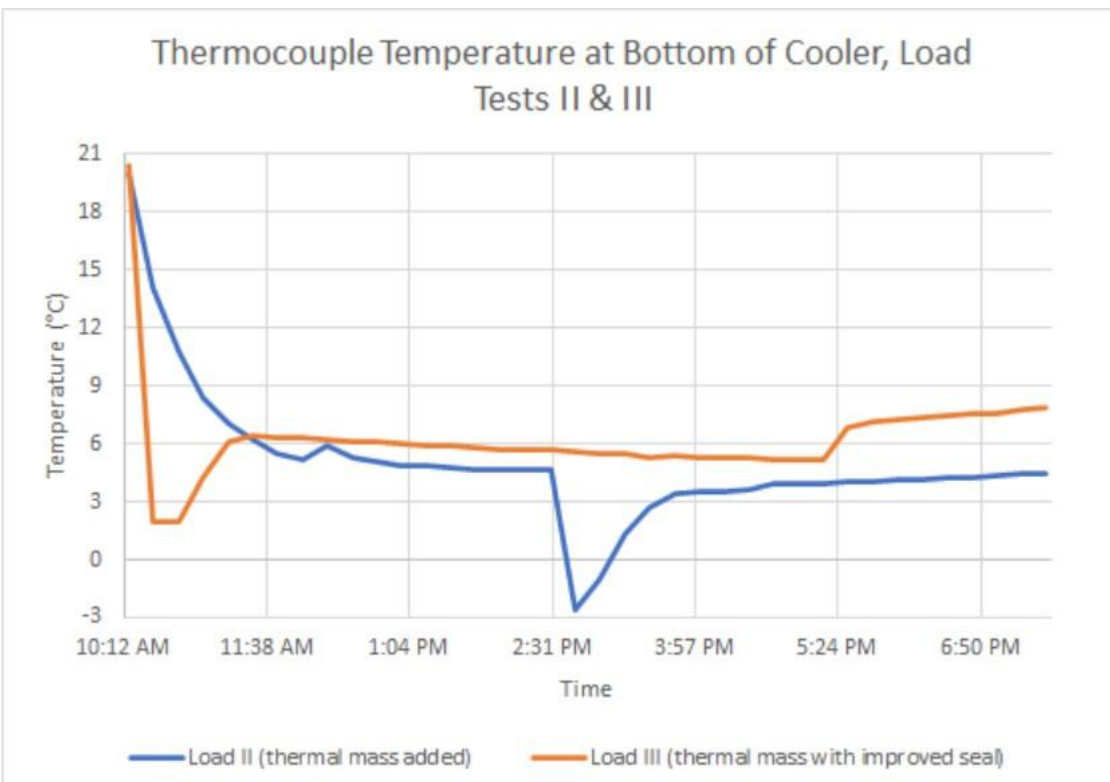

Fig. 34: Fluke 289 Thermocouple Temperature Sensor measurements at the bottom of thermoelectric cooler for load tests 2 and 3.

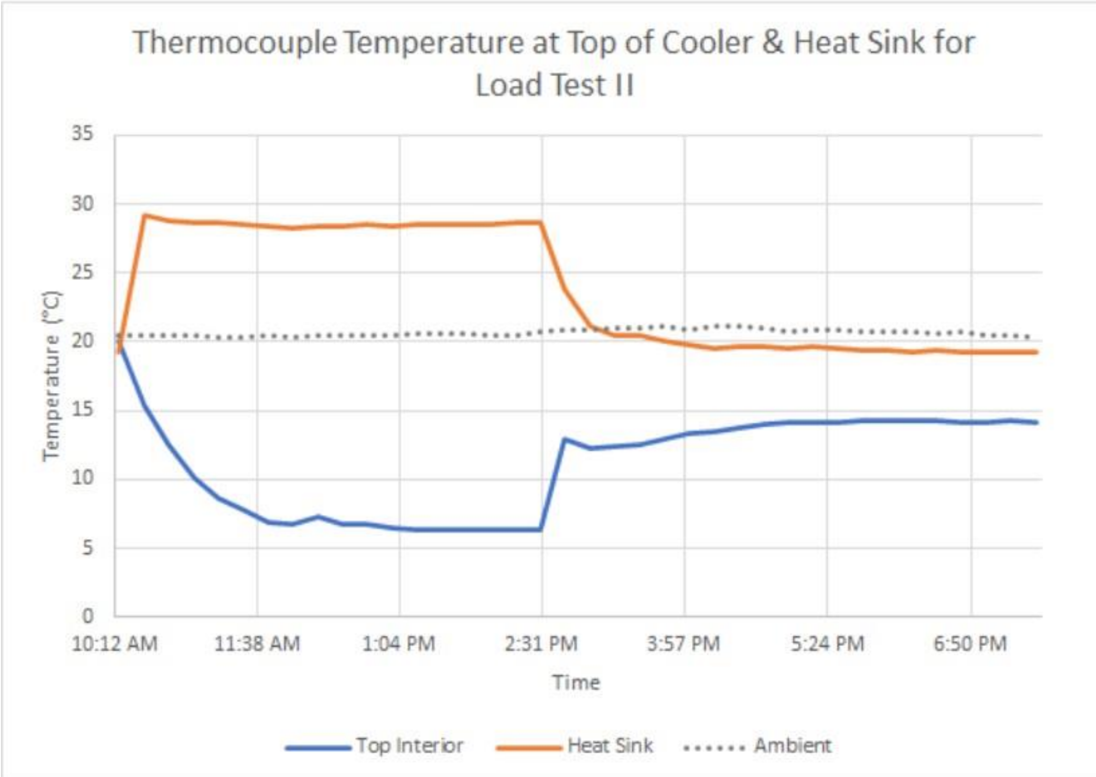

Fig. 35: Fluke 289 Thermocouple Temperature Sensor measurements for interior ceiling and external heat sink of the cooler for load test 3.

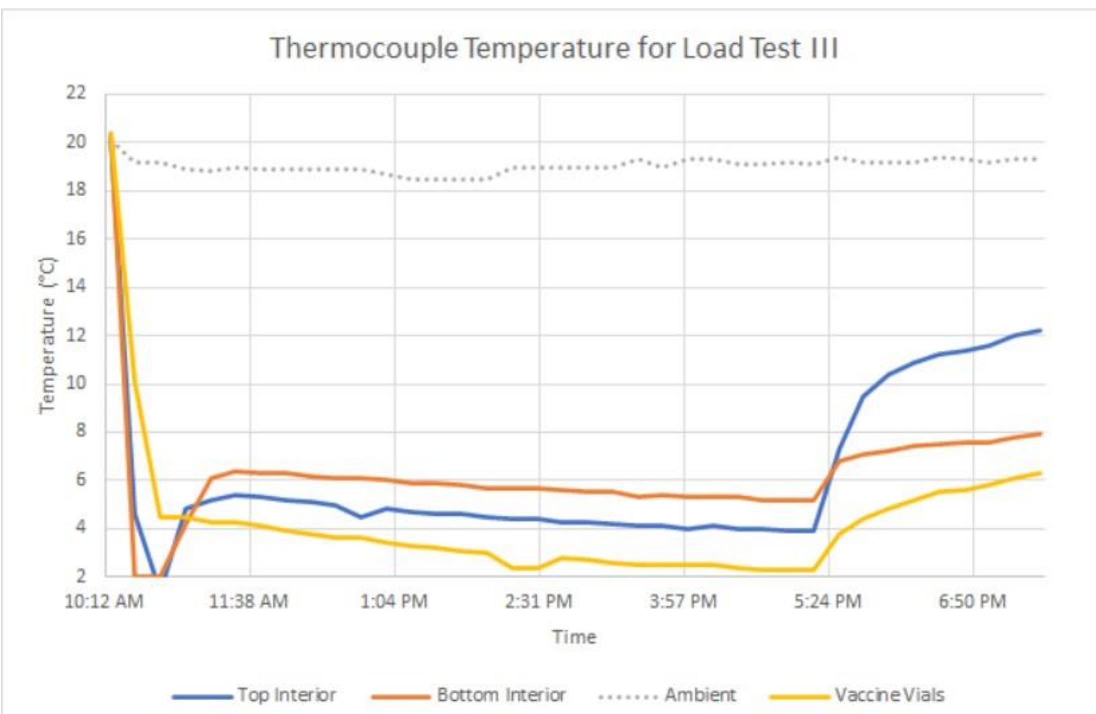

Fig. 36: Fluke 289 Thermocouple Temperature Sensor measurements for vaccine vials and top interior and bottom interior of thermoelectric cooler for load test 3.

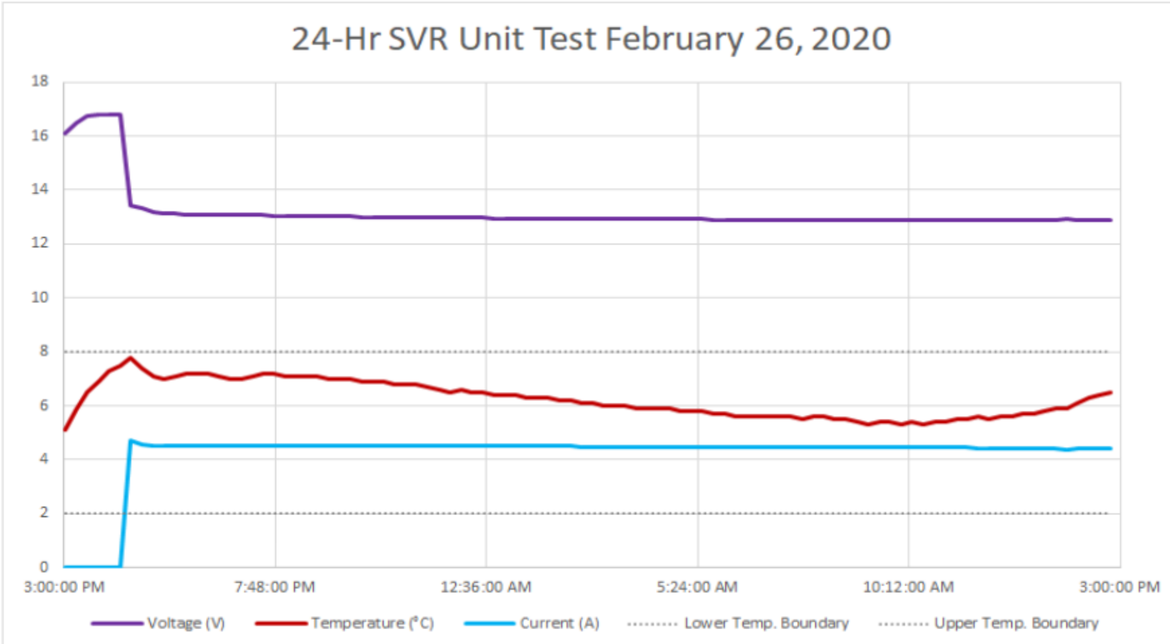

Fig. 37: Fluke 289 Thermocouple Temperature Sensor measurements for the voltage of the battery, temperature of the vaccine vials, and current supplied to the thermoelectric cooler for the 24-hour full SPVR system test. Please note that the input DC power from the DC SAS Power Supply was set at a pre-programmed mode to following the EN50530 testing standards.

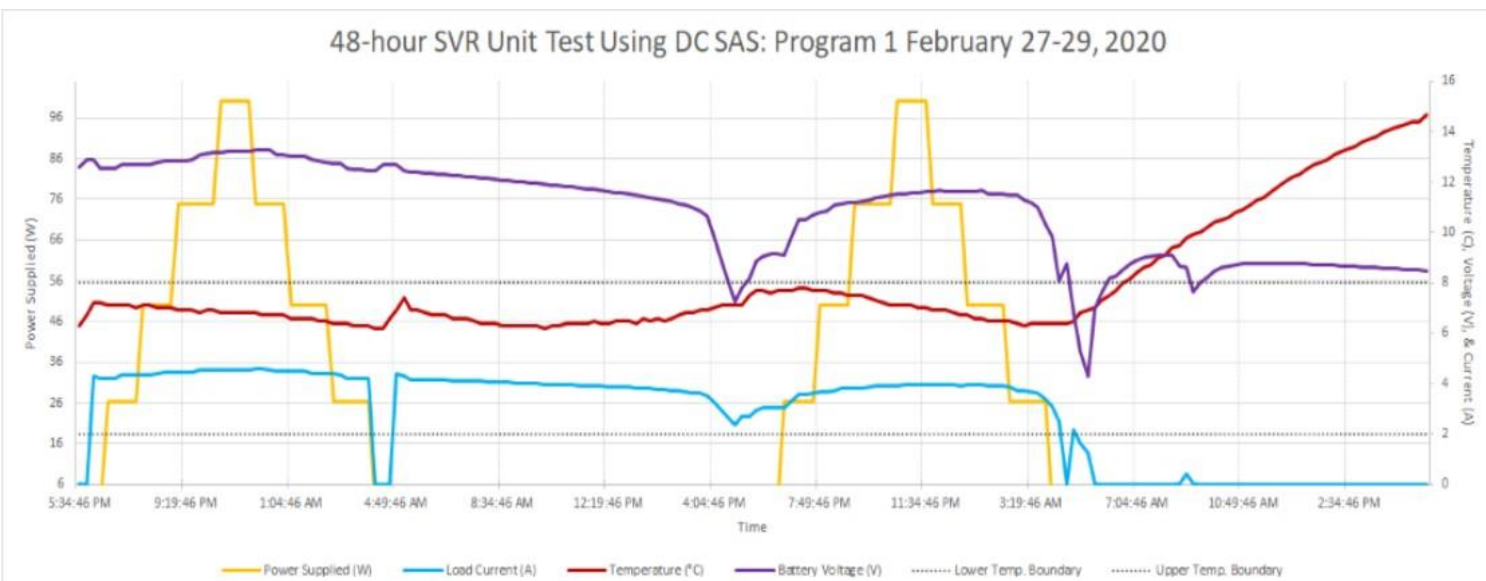

Fig. 38: Fluke 289 Thermocouple Temperature Sensor measurements for the voltage of the battery, temperature of the vaccine vials, and current supplied to the thermoelectric cooler for the first 48-hour full-PV system test.

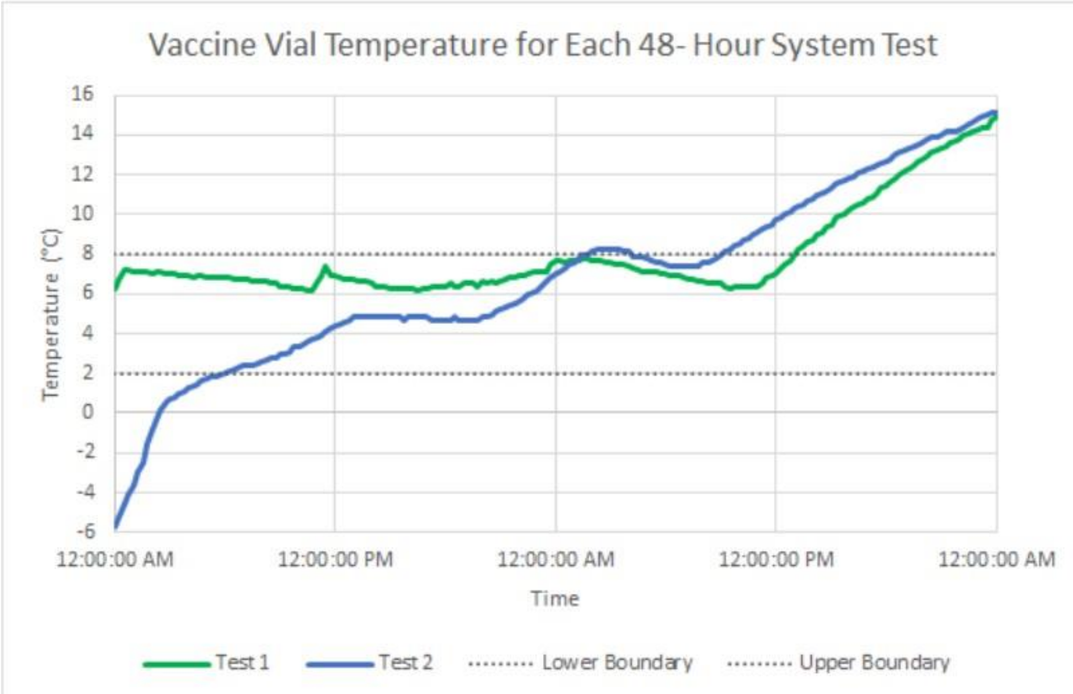

Fig. 39: Fluke 289 Thermocouple Temperature Sensor measurements for the vaccine vial temperatures for the first and second 48-hour full-PV system tests.

Appendix R: Extra Graphical Results for Load Test II

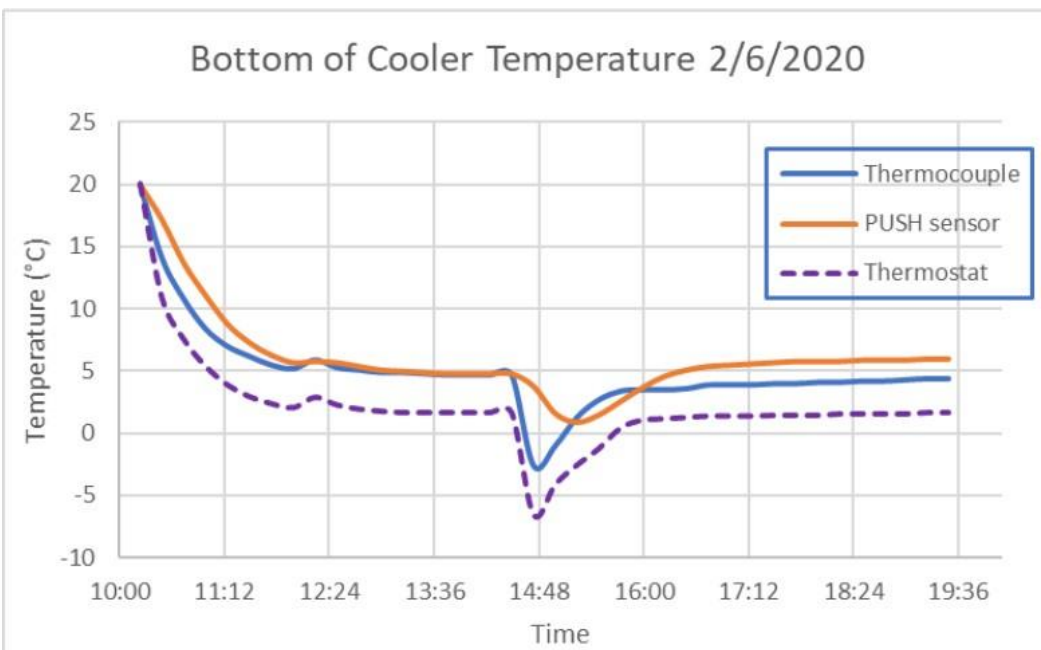

Fig. 40: PUSH temperature sensors and Fluke 289 Thermocouple Temperature Sensor measurements for the bottom of the thermoelectric cooler for load test 2.

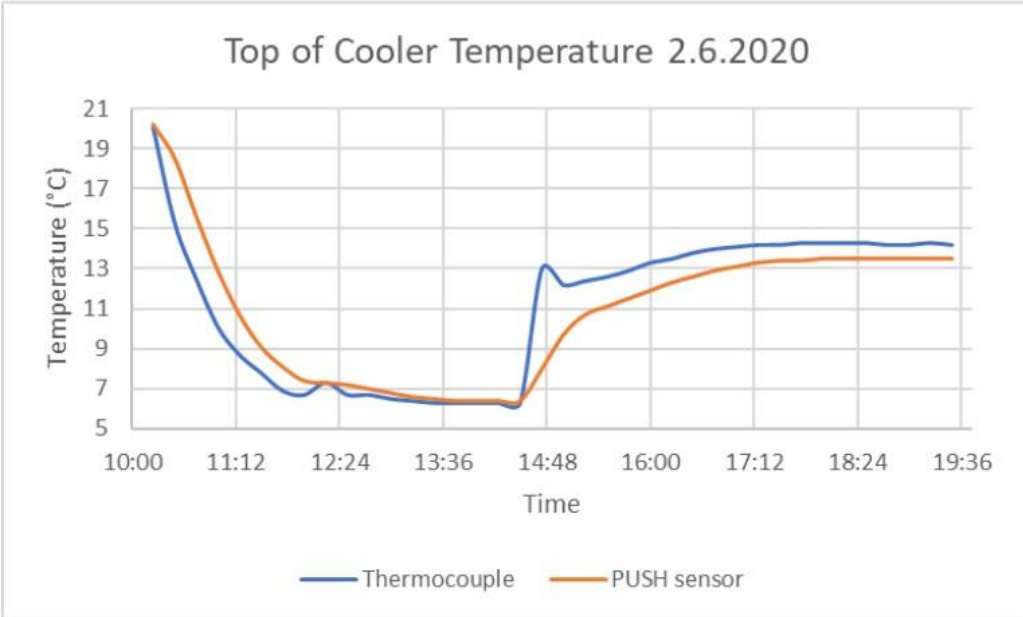

Fig. 41: PUSH temperature sensors and Fluke 289 Thermocouple Temperature Sensor measurements for the top interior portion of the thermoelectric cooler for load test 2.

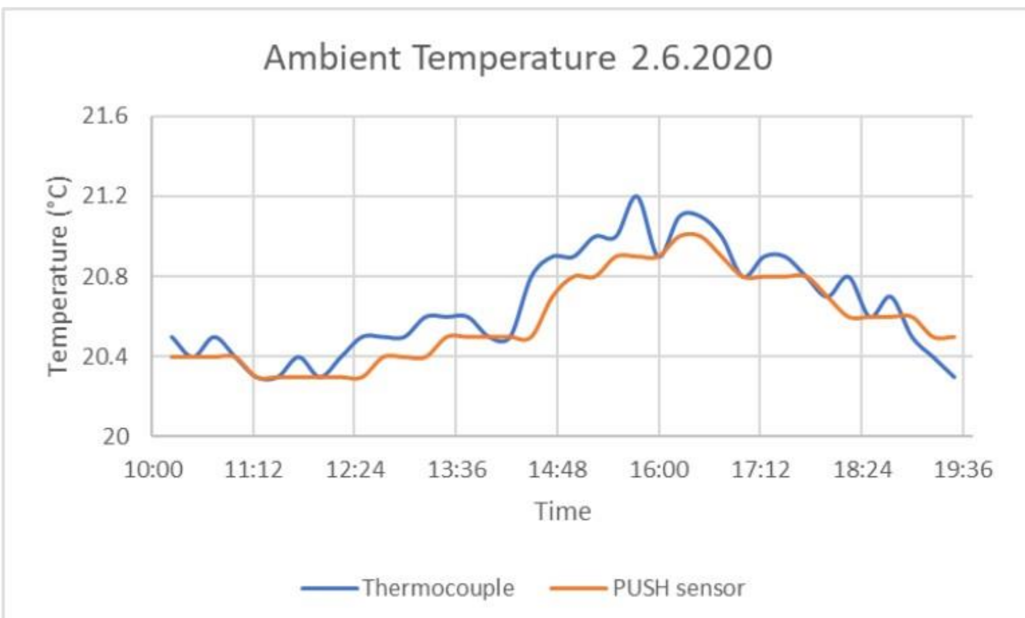

Fig. 42: PUSH temperature sensors and Fluke 289 Thermocouple Temperature Sensor measurements for the ambient temperature during load test 2.

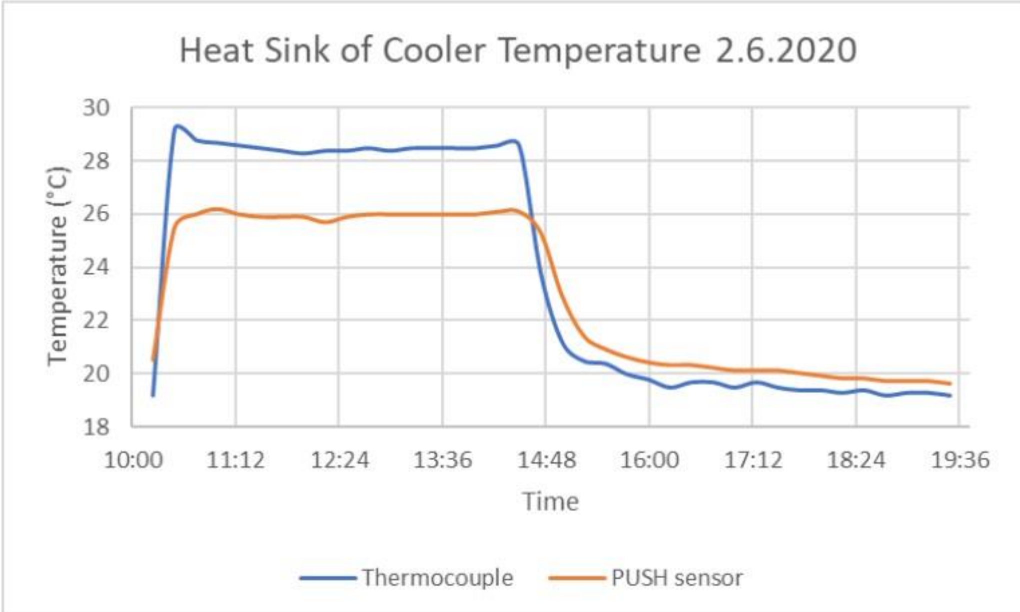

Fig. 43: PUSH temperature sensors and Fluke 289 Thermocouple Temperature Sensor measurements for the heat sink of the thermoelectric cooler during load test 2.

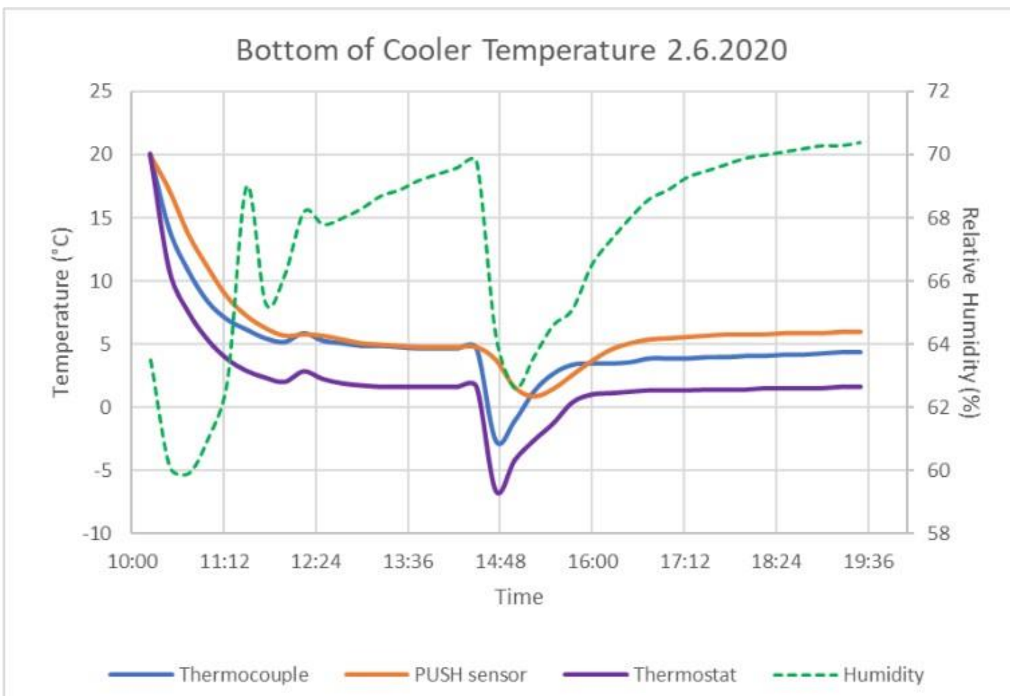

Fig. 44: PUSH temperature sensors and Fluke 289 Thermocouple Temperature Sensor measurements for the bottom interior of thermoelectric cooler during load test 2.

Appendix S: Possible Future Project Directions Stemming from this SPVR Project

1. **Testing system with High-Quality, Lightweight Monocrystalline or Polycrystalline PV Panels Versus a DC Simulated Solar Array Power Supply**
   a. Description of Idea: Sizing the PV Panel for the current system used in this project (based on the solar radiation of Portland, Oregon) and testing the viability of this system here would be one of the major goals for this type of project. Considering that Oregon has a significantly lower solar radiation value compared to Uttar Pradesh, India, the success

of these tests would increase the possibility that this system would be able to handle the solar conditions of Allahabad, India.

b. Aspect of Improvement (based on this project): This provides a more realistic idea of how the system will perform using actual solar conditions instead of replication of a solar curve using a DC SAS Power Supply. However, the DC SAS would still be needed as a comparison, but not as a basis for the implementation of this technology.

2. **Developing an SPVR System Using Ideal Components**
   a. Description of Idea: In the team's RBC proposal, we sized and specified a specific set of components, materials, and accessories that would provide large vaccine storage space; two battery systems to support refrigeration; extra energy storage to accommodate secondary loads (such as cell phone charging); a communication unit; ease of travel; and more days of system autonomy.
   b. Aspect of Improvement: Using materials and components that are closer to the actual build for Uttar Pradesh would give future capstone teams a better idea on how to address the issues and challenges involved with implementing a more robust system.
3. **Further Research into the Solar and Climate Data of Uttar Pradesh, India**
   a. Description of Idea: Having more detailed information regarding the hourly solar radiation, weather patterns, and climate during the optimal operation months for this technology allows for better simulation parameter settings for the DC SAS Power Supply and a better selection of solar PV panels.
   b. Aspect of Improvement: Further technologies (for future projects) could be researched and developed to use devices to optimize solar energy capture or integrate other renewable systems. For example, more efficient or customizable charge controller units could be built specifically for medical application purposes.
4. **SPVR System Modeling**
   a. Description of Idea: More detailed modeling of the SPVR system in terms of mechanical stability; physical build; thermal stability (with TEC operation included in the analysis); as well temperature impact on energy consumption would be beneficial for creating a more accurate prediction of how the TEC would operate in Uttar Pradesh. Computer simulations should account for the actual design and materials used for the build.
   b. Aspect of Improvement: Improved system modeling would allow for better comparisons between empirical tests and computer simulated data
5. **Expanded System Testing Parameters**
   a. Description of Idea: Performing comprehensive tests on various system parameters and components such as solar panel tilt angle, insulation type, battery type, wire resistance would provide future project teams with a more detailed characterization of the system.
   b. Aspect of Improvement: More comprehensive tests that take all parameters into account would provide a better understanding of the limitations of implementing this system in the cold-chain infrastructure of Uttar Pradesh, India.
6. **Expanded Economic Feasibility for Implementation**
   a. Description of Idea: The implementation of this project in Uttar Pradesh, India could see a higher rate of success if it benefits the local economies in that region.
   b. Aspect of Improvement: Determining the medical needs and key electronic/electrical-related necessities of Uttar Pradesh, India would serve as a means to understanding what type of technologies to incorporate with the SPVR unit that would make it more convincing for local medical facilities to use.
7. **Energy Efficiency of Off-Grid RE-based Vaccine Refrigeration**
   a. Description of Idea: Determining the technologies or improvements to existing technologies that could be developed to conserve energy for medical vaccine refrigerators could be the means to the development of a more compact and robust SPVR system. Research could also be made on how to extend the lifespan of RE systems for rugged conditions (i.e., cold-chain transportation in rural communities).
   b. Aspect of Improvement: Analysis and measurements that focus on energy consumption and usage statistics for solar-powered vaccine cooling systems could serve as the basis for projects that aim to improve the autonomy and durability of such systems.
8. **Modularization, Replacements, and Manufacturability of the SPVR System**
   a. Description of Idea: Once a more robust SPVR system has been developed, tested, and simulated for application in Uttar Pradesh, India, finding ways to make the system easy to set up, move, replace, and manufacture would be one of the future steps to expand the viability of this system in rural areas of India and other developing countries.
   b. Aspect of Improvement: Projects that focus on modularizing the build and making this system easily updatable & customizable for different conditions (I.e., in underdeveloped countries) could possibly support the wide-spread use of

this system.

9. **Creation of Housing/Case for Electrical Components of SPVR System**
    a. Description of Idea: This relates to the modularization idea where the prototype system is designed for easy access to electrical components. Future students could design and build a case to enclose the principal electronic components of the system.
    b. Aspect of improvement: Creating an enclosure would give a better sense of the space needed by the SPVR in cold-chain transport vehicles and community health centers.
10. **Research and Development to Expand the SPVR System to a Multi-Purpose Medical Unit**
    a. Description of Idea: If there is sufficient support for further development and refinement of the SPVR technology, further research could be done to expand the use of this system to other medical applications such as immediate response and relief efforts around the world (e.g. cooling units for food and medical supplies for areas affected by natural disasters such as Hurricane Katrina).
    b. Aspect of improvement: Research, development, and testing that is focused on expanding the operational range and capability of the ideal SPVR system for global relief applications for both developed and developing countries could possibly support the widespread use of this system.

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